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NASA Contractor Report 187206

TUBULAR COPPER THRUST CHAMBER DESIGN STUDY

FINAL REPORT

Pratt & Whitney
Government Engines & Space Propulsion
P.O. Box 109600
West Palm Beach, FL 33410–9600

May 1992

Prepared for
Lewis Research Center
Under Contract No. NAS3-23858

NASA
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FOREWORD

This technical report presents the results of a Tubular Copper Thrust Chamber Design Study. The study was conducted by the Pratt & Whitney (P&W)/Government Engines & Space Propulsion (GESP) of the United Technologies Corporation (UTC) for the National Aeronautics and Space Administration, Lewis Research Center under Contract NAS3-23858, Task Order C.2.

The study was initiated in October 1989 and completed in June 1990. Mr. John Kazaroff was the NASA Task Order Manager. The effort at P&W was carried out under Mr. James R. Brown, Program Manager, and Mr. Arthur I. Masters, Engineering Manager. Other individuals providing significant contributions in the preparation of the report were Donald E. Galler and Scott Chesla — Cycle Performance; James R. Black and Aaron R. Fierstein — Heat Transfer; Tim Ehlers — Mechanical Design; and Charles Ruby — Structural Analysis. Mr. G. Paul Richter was the orbit transfer vehicle (OTV) Program Manager.

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SECTION I
INTRODUCTION

A. BACKGROUND

Tube bundle construction is one of the least expensive, shortest lead time, and most developed means of fabricating rocket engine thrust chambers. Most production engine thrust chambers before the Space Shuttle Main Engine (SSME) were fabricated from tube bundles. At the high combustion pressures of the SSME, high material thermal conductivity is essential to minimize hot-wall thermal gradients. Copper is the only suitable construction material with adequate conductivity to meet this requirement. Since conventional tube bundle construction requires brazing, and conventional copper alloys cannot be brazed without a prohibitive loss in tensile strength, alternative means of producing copper thrust chambers (i.e., milled channel construction) had to be developed. This type of construction is very costly, requires extensive lead time, and produces serious low-cycle fatigue life limitations.

NASA-Lewis Research Center has pioneered the use of electroforming and plasma spraying as a means of bonding copper tube bundles without exposing the copper to the high temperatures associated with brazing. Pratt & Whitney (P&W) is currently looking at special copper alloys (e.g., GlidCop™ AL-15) that can be brazed without a large reduction in strength. The development of either or both of these bonding techniques will provide new approaches for combining the advantages of tubular chamber construction with those of high-conductivity copper.

The use of copper tubular thrust chambers is particularly important in a high-performance expander cycle space engine. High performance requires high combustion chamber pressure. Expander cycle engines are limited in chamber pressure by the amount of regenerative heat available to drive the turbomachinery. Tubular chambers have more surface area than flat wall chambers (milled-channel construction), and this extra surface area provides enhanced heat transfer for additional energy to power the cycle.

B. STUDY REQUIREMENTS

The Tubular Copper Thrust Chamber Design Study was divided into two primary technical activities: (1) a Thermal Analysis and Sensitivity Study and (2) a Preliminary Design of a selected thrust chamber configuration. The thermal analysis consisted of a statistical optimization to determine the optimum tube geometry, tube booking, thrust chamber geometry, and cooling routing to achieve the maximum upper limit chamber pressure for a 25,000-pound thrust engine. Two cycle types, a split expander cycle and full expander cycle with a regenerator, were considered. In optimizing the tube geometry, the following parameters were considered: tube diameter, tube wall thickness, the number of tubes, and the degree of tube taper. In optimizing thrust chamber size, chamber length, and contraction ratio were considered.

The range of variables considered was established as follows:

• Tube diameter	0.080 in. to a maximum based on structural limits and coolant velocity requirements
• Tube wall thickness	0.015 in. to 0.050 in.

• Degree of booking (ratio of tube height to width)	1.0 to 4.0
• Chamber contraction ratio (injector area to throat area)	2.5 to 5.0
• Number of tubes	As required based on geometric considerations above
• Chamber length	12.0 in. (required for combustion) or the length that provides maximum cycle power margin, whichever is shortest
• Tube taper	As required for optimum cooling.

In conducting the study, a thermal enhancement of 18 percent due to the increased surface area from the tubular geometry was assumed. The effect of increasing the assumed thermal enhancement to 30 percent was also evaluated.

The goal of the preliminary design was to define a tubular thrust chamber that would demonstrate the inherent advantages of copper tube construction in full-scale hardware. The Advanced Expander Test Bed (AETB) was selected as the most appropriate vehicle for the demonstration. The AETB is being designed with a 25-percent uprated design point relative to its normal operating point. The design point is 25,000 lb thrust at 1500 psia chamber pressure, and the normal operating point is 20,000 lb thrust at 1200 psia. The thrust chamber has a contraction ratio of 3 to 1 and a conical exhaust nozzle expanding to an area ratio of 2 to 1.

The AETB configuration requirements are similar to the chamber that was defined in the split expander cycle portion of the thermal analysis and sensitivity study. These requirements are summarized in Table 1. At NASA's request, the thermal enhancement for the tubular construction was assumed to be 40 percent in the first 10 in. of the combustor, 20 percent near the nozzle throat, and 30 percent in the convergent section.

TABLE 1. — TUBULAR COPPER THRUST CHAMBER RECOMMENDED DESIGN PARAMETERS

Injector End Diameter (in.)	5.68
Throat Area (sq in.)	8.45
Contraction Ratio	3.0
Length-Injector-to-Throat (in.)	12.0 — 15
Nozzle Expansion Ratio	2.0
Coolant Bypass Flow (%)	50

C. THERMAL ANALYSIS RESULTS

The thermal analysis and sensitivity study was conducted in two parts. First, a sophisticated optimization procedure was used to find an optimum tube geometry for maximum chamber pressure. The optimization process considered the impact of changes in tube and thrust chamber geometry on total heat pickup and pressure drop, and the resulting effect on the engine cycle in terms of achievable chamber pressure. Both the split expander cycle and full expander cycle with regeneration were considered. The study assumed the heat transfer enhancement associated with the tubular geometry was 18 percent. Practical design limits were set on the turbomachinery operating conditions, and the fuel pump was limited to three pump stages.

The second part of the analysis consisted of sensitivity studies to determine the impact of changing some of the assumptions that went into the original optimization. The two most significant variables in the sensitivity study were found to be the assumed heat flux enhancement for tubes and the limitation on the number of fuel pump stages.

A comparison of achievable chamber pressure for the two cycles with 18-percent and 30-percent heat transfer enhancement is shown in Table 2. An enhancement of 18 percent produces an increase in achievable chamber pressure of 195 psi (11 percent) for the split expander cycle and 433 psi (25 percent) increase for the full expander cycle with a regenerator. An increased enhancement of 30 percent provides no additional benefit because of thrust chamber heat transfer limits in the regenerator cycle and fuel pump tip speed limits in the split expander cycle.

TABLE 2. — EFFECT OF TUBULAR CHAMBER HEAT TRANSFER ENHANCEMENT ON UPPER LIMIT CHAMBER PRESSURE

	Milled Channel Chamber	*Tubular Chamber Enhancement*	
		18%	*30%*
Split Expander Cycle Chamber Pressure (psia)	1560	1755	1758
Full Expander With Regenerator Chamber Pressure (psia)	1717	2150	2144

The split expander cycle fuel pump tip speed limitation can be overcome by addition of a fourth fuel pump stage to redistribute stage head rise. Table 3 shows upper limit chamber pressure for split expander cycles with three- and four-stage fuel pumps and 18-percent and 30-percent enhancement. With a four-stage fuel pump and 30-percent enhancement the upper limit chamber pressure is increased to 2162 psia.

TABLE 3. — THREE- AND FOUR-STAGE FUEL PUMP COMPARISON IN THE SPLIT EXPANDER CYCLE

Enhancement (%)	*3-Stage Fuel Pump*	*4-Stage Fuel Pump*
18	1755	1917
30	1758	2162

D. PRELIMINARY DESIGN SUMMARY

The preliminary design effort produced a layout drawing of a tubular thrust chamber suitable for testing in the AETB. The chamber liner has 140 copper tubes that are tapered and booked to a near optimum coolant flowpath. An electroformed jacket around the tube bundle is used to join the tubes and contain the thrust chamber pressure. The manifolds and attachment flanges are formed from Inconel 909 to minimize thermal growth differences between the thrust chamber and the injector and conical nozzle. Two alternate methods of attaching the manifold assemblies (welding to the electroformed jacket and electroforming around the attachment points) are included on the layout. A sketch of the chamber is provided in Figure 1.

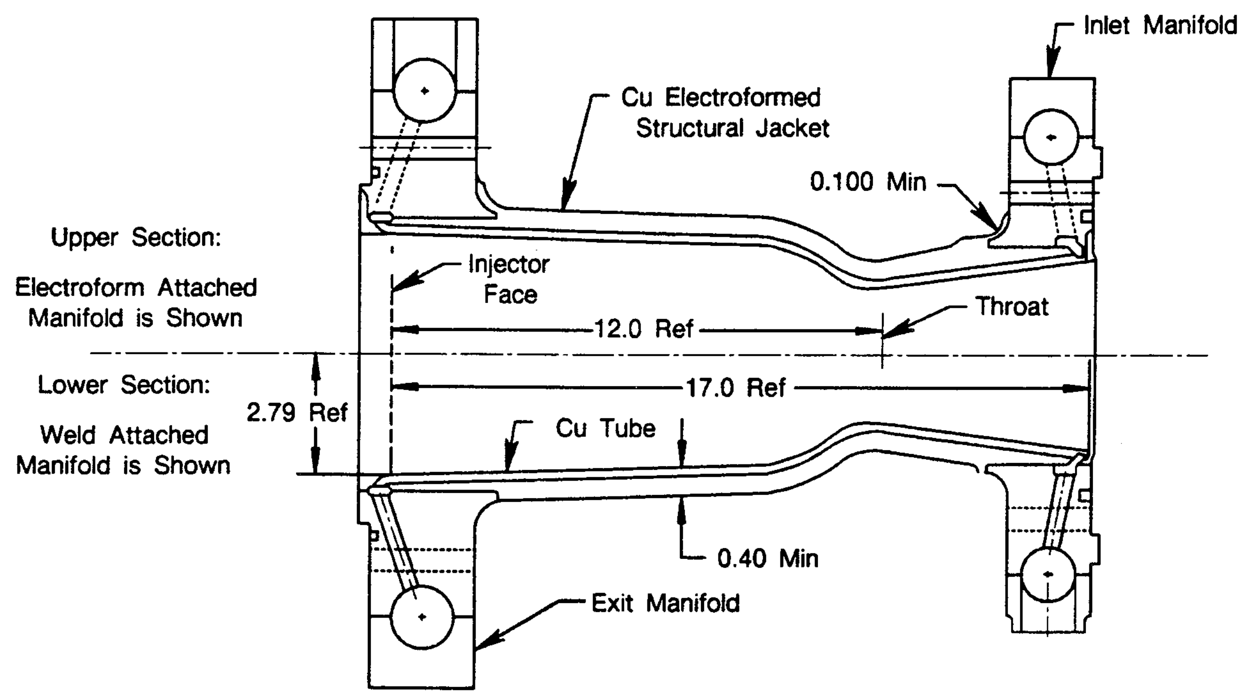

Figure 1. Advanced Expander Test Bed Copper Tubular Combustion Chamber

The combustion chamber length from the injector face to the nozzle throat is 12.0 inches, 3.0 inches shorter than the AETB milled channel chamber. Based on the assumed heat transfer enhancement of 40 percent near the injector and 20 percent near the nozzle throat, this reduced-length chamber is predicted to provide a 5-percent increase in overall heat transfer and a 15-percent reduction in coolant pressure drop (including the AETB conical nozzle), as shown in Table 4. Testing this chamber in the AETB would provide a significant cycle benefit to the AETB and would confirm the inherent advantages of tubular chamber construction, even though the performance improvements measured in the AETB would be less than could be achieved in an engine specifically designed for a tubular chamber.

TABLE 4. — COMPARISON OF TUBULAR AND MILLED CHANNEL AETB THRUST CHAMBER COOLING

	Length (in.)	*Total Heat Transfer (Btu)*	*Total Coolant Pressure (psi)*
Milled Channel	15	12,420	501
Copper Tubes	12	13,010	425

SECTION II
STUDY PROCEDURES

A. OPTIMIZATION METHODOLOGY

Rocket cycle optimization is a complex procedure because of the number and range of engine and thrust chamber design variables that must be considered. To establish a thrust chamber design that best meets a set of requirements, various configurations must be selected and key design variables established for each configuration. An engine cycle analysis is then performed for each combination of independent variables for each configuration selected, and the capability of each system defined. The capability is then compared to the previously established requirements and figure-of-merit. Iterations for the most promising configuration are performed to refine system capability, and the optimum variable combinations in the region of defined interest must be determined. This process of system definition with multiple design variables can be lengthy and can involve large amounts of data. To reduce the quantity of data and required time, a computerized system statistical optimization methodology to define the thrust chamber configuration was employed.

The statistical optimization tool used during this study was developed by Pratt & Whitney (P&W) during the Airplane Response Engine Selection (ARES) Program (Reference 1). Briefly, the methodology uses the following:

- A design selector to select independent variable combinations and levels
- Performance simulators to simulate thrust chamber and engine performance and determine overall system performance levels
- A data interpolator that correlates the system performance output from the performance simulator through the use of regression analysis
- An interpreter that interrogates the performance surfaces that result from the regression equations. The interpreter incorporates optimizer logic that uses a search technique to vary independent variable levels to maximize system performance according to a selected figure-of-merit.

1. Description of Methodology

Combinations and levels of the key independent design variables are selected for use in defining overall system performance hardpoints. Levels and combinations of both thrust-chamber-associated design variables (e.g., aspect ratio) and engine-associated design variables are selected.

Engine performance data to be included in the cycle analysis are generated for all selected engine-associated design variable levels and combinations. An engine simulation deck is then used to establish the system performance levels. The output from the engine simulation deck in terms of the dependent variable levels (chamber pressure, pump pressure, turbine temperature, etc.) associated with the combinations and levels of the independent variables (contraction ratio, inlet temperature, etc.) comprise the database for the ARES methodology. Since the database includes both engine associated and thrust chamber associated variables, interaction between engine and chamber variables may be studied.

A regression program is used to fit hypergeometric surfaces for any desired dependent variable. The use of the regression equations then permits interpolation of dependent variable

solutions for independent variable combinations in addition to those comprising the database to be determined. Thus, the expanded database (the regression equations) actually constitute a series of multidimensional surfaces (one for each dependent variable regressed) where the number of dimensions is the number of independent variables in the regression equations. Second-order polynomial regression equations are used for all surface fits.

The optimization program then searches the database to find an optimum engine/thrust chamber design combination by minimizing a specified figure-of-merit (pump pressure) or maximizing a payoff function (chamber pressure) subject to constraints on specified functions (e.g., hot-wall temperature). The optimization analysis uses the surface fit functions provided by the regression equations for its payoff and constraint functions. Any number of optima may be found and analyzed by repeated applications of the procedure with different combinations of constraints and payoff functions. Since this procedure is entirely computerized, the ARES methodology offers rapid assessment of alternative payoff functions, penalty functions, or constraint bands. Also, because the number of variable combinations can be large, the methodology can incorporate both engine and thrust chamber independent variables. Thus, the database includes engine/chamber interactive effects.

2. Design Selector

A modified central composite design (CCD) data selection pattern was used in this study. Central composite design patterns in many variations are in common use in response surface methodology. The pattern for a three-variable case can be visualized in three dimensions as a cube with a data point at each corner, a point in the center of each face, and a point in the center of the cube (Figure 2).

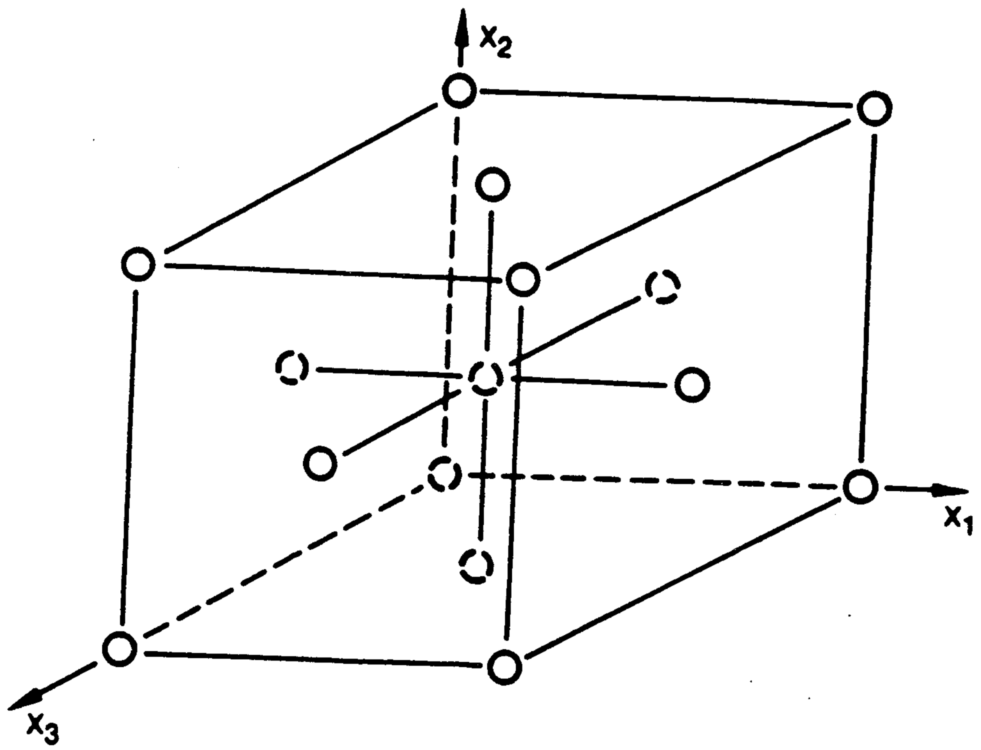

Figure 2. Isometric View of Three-Variable Central Composite Design Pattern

With this design pattern, many cross-plots can readily be made and cross-coupling terms defined. As the number of independent variables increases, the number of corner points goes up

dramatically (2n), while the number of face points only increases by 2n. Reducing the number of corner points to reduce the cost of data generation, therefore, becomes expedient. The equation for number of points becomes:

$$\frac{2^n}{2^k}+2n+1$$

for $k = 0$ All corner points are used (full replication)
$k = 1$ one-half the corner points are used (half replication)
$k = 2$ one-quarter of the corner points are used (quarter replication)
$k = 3$ one-eighth of the corner point are used (eighth replication)

A five-variable data pattern is presented in Figure 3.

The solid points shown are included in the half replication pattern, while all the points shown are used in the full replication pattern. In data generation, the low (L), mid (M), and high (H) values of a variable are not always the same. At some of the corner points where upper and lower limit combinations of a variable are to be used, a converged solution is not always obtainable.

3. Regression Analysis Method

The regression technique employed during this study is a classical least squares procedure using a pivoting matrix inversion subroutine. This particular computerized regression routine is capable of handling multiple variable, noninteger power, polynomial forms. The routine has backward elimination capability using a t-status criteria. Normalization of variables was not used, since normalization was determined to have no impact upon the accuracy of surface fits.

The regression routine was modified and incorporated into a computer program with automated data handling capabilities, as a convenience for handling output and for evaluating methods developed in this study. The capabilities include the following:

- Transformation and retransformation of dependent variables for both regressed and check data

- Calculation of quadratic solutions for independent variables from 2nd order polynomial regression equation forms

- Error statistic analysis for indirect methods that use regressed variables as independent and dependent variables.

4. Selection of Study Variables

The initial step in the study was to select the independent variables for the copper tubular thrust chamber heat transfer analysis. Seven parameters were chosen (Table 5). Figures 4, 5, and 6 present the CCD matrix used for the thrust chamber analysis.

BPR		L									M									H								
TR		L			M			H			L			M			H			L			M			H		
Sweep		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
H	H	●		○				○		●										○		●				●		○
	M														●													
	L	○		●				●		○										●		○				○		●
M	H														●													
	M					●						●		●	●	●		●						●				
	L														●													
L	H	○		●				●		○										●		○				○		●
	M														●													
	L	●		○				○		●										○		●				●		○
W/S	T/W																											

L = Low
M = Medium
H = High

} Values of Variables Used in Experiment

Note:
Full Replication: All Points
Half Replication: Solid Points

Figure 3. Schematic of Five-Variable CCD Pattern

PC	1600									1900									2200											
CR	2.5			3.5			5.0			2.5			3.5			5.0			2.5			3.5			5.0					
ZI	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	ASP	WC	TN
	●		○				○		●										○		●				●		○	1.0	3.5	80
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																												2.5		
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	○		●				●		○										●		○				○		●	1.0	3.5	120
																												2.5		
	●		○				○		●										○		●				●		○	4.0		
																												1.0	5.8	
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																												2.5		
	○		●				●		○										●		○				○		●	4.0		

Figure 4. Preliminary Advanced Thrust Chamber Optimization for $T_c = 110°R$

PC	1600									1900									2200											
CR	2.5			3.5			5.0			2.5			3.5			5.0			2.5			3.5			5.0					
ZI	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	ASP	WC	TN
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																												1.0	8.0	
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																												4.0		

Figure 5. Preliminary Advanced Thrust Chamber Optimization for $T_c = 250°R$

PC	1600									1900									2200									ASP	WC	TN
CR	2.5			3.5			5.0			2.5			3.5			5.0			2.5			3.5			5.0					
ZI	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20			
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Figure 6. Preliminary Advanced Thrust Chamber Optimization for T_c= 400°R

TABLE 5. — COPPER TUBULAR THRUST CHAMBER VARIABLES

Chamber Pressure (PC) — psia	1600	1900	2200
Contraction Ratio (CR)	2.5	3.5	5.0
Chamber Length (ZI) — in.	12	16	20
Tube Number (TN)	60	90	120
Coolant Flow (WC) — lb/sec	3.5	5.8	8.0
Aspect Ratio (ASP)	1.0	2.5	4.0
Coolant Inlet Temperature (TC) —°R	110	250	400

B. THERMAL ANALYSIS

The thermal analysis was conducted using P&W's nozzle/thrust chamber cooling design computer code. The code is designed to analyze tubular or machined thrust chambers and convectively cooled tubular, film-cooled, and radiation-cooled nozzles. The combustion side heat transfer rates are based on the Mayer Integral Method, to calculate the heat transfer coefficient, and enthalpy driving potential, to define a driving temperature. Enthalpy driving potential is the difference between the free-stream stagnation enthalpy and the enthalpy level at the wall. The stagnation enthalpy of the combustion gasses is strongly dependent on chamber pressure due to dissociation of the combustion products. Dissociation of the combustion products occurs at temperatures above 3000°R. At temperatures below 3000°R, the energy state can be represented adequately with specific heat.

The formulation used in the code for the combustion side heat transfer is as follows:

The following nomenclature is used in the subroutine:

area	in2	comb. flow area
c_m	dimensionless	constant in combustion eqn
H_{comb}	Btu/in2-sec-R	combustion heat transfer coefficient
R	in.	comb. wall radius
s	in.	contour length from injector face
T	deg R	comb. gas temperature
V	in/sec	comb. gas velocity
wma	lbm/sec	comb. gas flow
z	in.	axial length referenced to the throat.

The following property variables are used in the subroutine:

C_p	Btu/lbm-R	specific heat
ρ	lbm/in3	density
h	Btu/lbm	enthalpy
k	Btu/in-sec-R	conductivity
μ	lbm/in-sec	viscosity
Pr	dimensionless	Prandtl number.

Two values of C_p, k and μ are input with corresponding temperatures and a log-log curve fit is applied. The Prandtl number is calculated at a given temperature by the equation:

$$Pr = \mu \times C_p/k$$

A reference enthalpy (h_{ref}) and a corresponding reference temperature (T_{ref}) are input along with a stagnation enthalpy curve (h_o-vs-z) which is equivalent to a stagnation temperature curve.

The three temperature locations used are:

f	comb. film (Eckert reference)
i	comb. infinity (bulk)
w	comb. wall.

According to the reference the heat transfer coefficient is

$$H3 = \frac{(c_m \times R^{1/4} \times B^{5/4} \times Pr_f^{-2/3} \times \rho_i \times C_{pf} \times V_i)}{\int_o^s (R \times B)^{5/4} \times \rho_i \times V_i \times \mu_i^{-1} \delta s)^{1/5}}$$

where,

$$B = (\mu_i/\mu_f)^{-1/5} \times (T_i/Tf)^{4/5}.$$

The denominator of the equation is referred to as the contour integral and has been found to be fairly insensitive to wall temperature. To simplify the computer program this is calculated in front of the heat transfer calculation and a contour integral curve is generated (int-vs-z).

The reduced form of the denominator, assuming finite steps from the injector face and wma/area = $\rho_i \times V_i$, for a given wall location is:

$$con = \frac{(R^{5/4} \times \mu_f^{1/4} \times T_i \times wma \times \Delta s)}{(\mu_i^{5/4} \times T_f \times area)}.$$

and

$$int_s = (con + (int_{s-1}^5))^{1/5}.$$

The initial int at the injector face is input using the formula:

$$int_{s0.0} = \left[\frac{(2 \times wma \times R_{inj}^{1/4})}{(\pi \times \mu_i)}\right]^{1/5}$$

where,

R_{inj} = comb. wall radius at injector face.

The numerator of the equation is calculated at the axial station being run. The reduced form of the equation with wma/area = $\rho_i \times V_1$ is:

$$H3 = \frac{(c_m \times R^{1/4} \times (\mu_f/\mu_i)^{1/4} \times T_i \times C_{pf} \times wma)}{(int_z \times Pr_f^{2/3} \times area)}$$

At present, analytical matching of data indicates a $c_m = 0.0296$.

Note: for a constant R = 1.0 these equations reduce to curved plate heat transfer.

To account for dissociation effects, enthalpy is used instead of temperature. Thus:

$$H_{comb} = H3/C_{pf}$$

and

$$q'' = H_{comb} \times edp$$

where,

$$edp = h_o - \Delta h_k \times (1.0 - Pr_f^{1/3}) - h_{ref} + C_{pref} \times (T_{ref} - T_{wall})$$

$$\Delta h_k = \frac{V_i^2}{7.21 \times 10^6}$$

A Mach number profile may be input which overrides the internal one-dimensional calculation. The input Mach number is used to calculate static pressure, hot gas velocity, and an aerodynamic area ratio (AAR). This is the area ratio at which the Mach number would occur in a one-dimensional flow field. The AAR is used to adjust the area term in the Mayer integral.

The combustion efficiency and the heat release of the chemical reaction define the local hot gas energy state for heat transfer. The energy intensity increases as the reaction process progresses through the chamber. The energy states and corresponding heat transfer driving potential are lower near the injector. The energy release profile can be generated based on theoretical behavior, or it can be input from available data. Although generally small relative to the convective heat flux component, the hot gas radiation component is evaluated within the P&W Rocket Thermal Design System, using a method formulated by Prof. A. H. Lefebvre, of Purdue University.

The internal wall thermal analysis procedure used within the computer code accounts for passage curvature, surface roughness, and large wall-to-coolant bulk temperature differences on the convective heat transfer coefficient of the coolant.

The coolant heat transfer and pressure loss formulation is:

A h_{cool}-vs-wall temperature curve is generated for a given axial location by executing the heat transfer coefficient subroutine within a loop while varying only the wall temperature.

The input for the coolant side subroutine is as follows:

d_h	in	hydraulic diameter
g	lbm/sec-in2	coolant mass velocity
P	psia	coolant static pressure
T_b	Rankine	bulk coolant temperature
T_w	Rankine	coolant wall temperature.

Other important variables are as follows:

H_{cool}	Btu/in2-sec-R	coolant heat transfer coefficient
q''	Btu/in2-sec	coolant heat flux
vel	ft/sec	coolant velocity.

The property variables used in the subroutine are as follows:

C_p	Btu/lbm-R	specific heat
ρ	lbm/in3	density
k	Btu/in-sec-R	conductivity
μ	lbm/in-sec	viscosity.

The three temperature locations used are as follows:

b	coolant bulk
f	coolant film
w	coolant wall.

The coolant film temperature is calculated using the following equation:

$$T_f = .5 \times T_w + (.5 \times T_b)$$

The heat transfer coefficient equation for hydrogen is defined by the following equation:

$$H_{cool} = 0.0227 \times Re_f^{0.8} \times Pr_f^{0.4} \times (\rho_f/\rho_b)^{0.8} \times (k_f/d_h) \times term$$

where,

$$term = 1. + .01457 \times \frac{(\mu_w \times \rho_b)}{(\mu_b \times \rho_w)}$$

$$Re_f = g \times d_h/\mu_f$$

$$Pr_f = \mu_f \times C_{pf}/k_f.$$

Local H_{cool} coefficients are adjusted for entrance, wall roughness, and curvature effects:

$$H_{cool} = H_{cool} \times ENH_{ent} \times ENH_{wall} \times ENH_{curv}.$$

The entrance effect is calculated by the following equation:

$$ENH_{ent} = 1 + \frac{(2 \times d_h)}{(x + d_h/2)}$$

where,

x = passage length.

The wall roughness effect is calculated by the following empirical equations:

$$eps = Re_b \times \sqrt{(c\int_i/2)} \times \varepsilon/d_h$$

$$prod1 = 3.074047 - 0.24377728 \times \text{antilog } eps - 0.5335861 \times \text{antilog } Pr_b$$

$$prod2 = 0.19007 + 0.02572894 \times \text{antilog } eps$$

$$prod3 = 0.838 \times Pr_b^{prod1} \times eps^{prod2}$$

$$stp_i = \frac{(c\int_i/2)}{(1 + \sqrt{(c\int_i/2)} \times prod3)}$$

if hfropt = 0, then $ENH_{wall} = 1$

if hfropt = 1, then $EHN = \dfrac{stp_1}{stp_2}$

if hfropt = 2, then $ENH_{wall} = 1 + .4 \times (stp_1/stp_2)$

where,

ε = absolute wall roughness

cf_i = the Moody friction factor at

$i = 1$ -- > rough wall, ε input
$i = 2$ -- > smooth wall, $\varepsilon = 0.000001$.

The curvature effect is calculated externally and input as a ENH_{curv}-vs-z curve. This multiplier is applied only to the passage bottom in the thermal skin; In the tube geometry, it is applied at its maximum at the tube bottom and linearly ratioed back to 1 at 90 degrees from the bottom.

The downstream static enthalpy and pressure are calculated using a control volume analysis. The two loss factors are friction and momentum:

$$P_1 = P_0 - \Delta P_{frict} - \Delta P_{mom}.$$

The frictional pressure loss is derived from the following equations:

$$\Delta P_{frict} = \left(\frac{(4 \times cf \times \Delta x)}{d_h}\right) \times \left(\frac{\rho \times vel^2}{2 \times g_c}\right)$$

$$\dot{m} = \rho \times area \times vel$$

$$d_h = \frac{4 \times area}{W_p}.$$

Combining the above equations, separating for upstream and downstream, and dimensionalizing for units:

$$\Delta P_{frict} = \left(\frac{\dot{m}}{24 \times g_c}\right) \times (\Delta x/2) \times \left(\frac{(c\int_0 \times vel_0 \times W_{p0})}{area_0^2} + \frac{(c\int_1 \times vel_1 \times W_{p1})}{area_1^2}\right).$$

The pressure loss due to curvature effects is accounted for by enhancing the friction coefficient using the following equations:

$$C_{turn} = 1 + 0.075 \times Re_b^{25} \times \left(\frac{d_h}{2 \times r_c}\right)$$

$$C\int_{new} = c\int_{old} \times C_{turn}$$

where,

r_c = passage wall curvature radius.

The momentum pressure loss is derived from the following incompressible equation:

$$\Delta P_{mom} = \frac{\rho \times vel^2}{2 \times g_c}$$

Combining with continuity, separating upstream and downstream, and dimensionalizing for units:

$$\Delta P_{mom} = \left(\frac{\dot{m}}{24 \times g_c}\right) \times (vel_1/area_1 - vel_0/area_0).$$

Now, since ρ = constant:

$$vel_1/area_0 = vel_0/area_1 \text{ and,}$$

$$\Delta P_{mom} = \left(\frac{\dot{m}}{24 \times g_c}\right) \times (1/area_1 - 1/area_0) \times (vel_1 - vel_0).$$

Inlet and exit manifold losses are calculated based on input loss coefficients and the coolant velocity in the coolant passage.

Two-dimensional conduction effects are automatically evaluated within the program using a finite-element model to give tube wall temperature distributions and coolant heatup. The effect of boundary layer buildup between the tubes of a tubular chamber is taken into account by using a simplified model that restricts the effective heat transfer area to some fraction of the exposed surface area. With this model, the maximum heat transfer enhancement is 57 percent ($\pi/2$). An enhancement of 57 percent would therefore assume no losses due to boundary layer buildup between the tubes. At the other extreme, assuming heat transfer over 64 percent of the exposed tube surface produces a heat flux equivalent to a flat plate (i.e., no enhancement).

For the parametric studies, an exposure of 73 percent was used for the chamber and nozzle. The 73-percent tube exposure results in an 18-percent heat transfer enhancement over a smooth wall. The 18-percent enhancement agrees well with RL10 test data. After the parametric studies were completed, individual cycle points were evaluated for 30-percent enhancement (82-percent exposure).

Based on preliminary studies, a single-pass counterflow tubular copper chamber and a pass-and-one-half parallel flow Haynes 230 nozzle were selected for the parametric study. The break point between the chamber and nozzle was set at an expansion area ratio of 6.5 to 1. The chamber and nozzle are cooled in series with the chamber being cooled first.

To reduce the number of tube geometry variables in the parametric study the following ground rules were set:

- The tubes had a variable wall thickness. The thickness was set at 0.015 in. at the throat (minimum wall thickness) for all cases. The wall thickness was set at the inlet manifold to give a pressure stress up to 90 percent of the yield strength up to a maximum thickness of 0.050 in. The thickness was varied linearly from the inlet manifold to the throat. A constant wall thickness was used from the throat to the injector unless allowable stress was exceeded. Where pressure stresses were exceeded, the same ground rules were applied upstream of the throat as downstream.

- The amount of tube booking or tube aspect ratio (ASP) was set at the throat and varied linearly from the throat to the injector and inlet manifold unless an ASP of 1 was reached. If an ASP of 1 was reached, the tube was tapered the rest of the way.

- The break point between the nozzle and chamber was set at an expansion area ratio of 6.5 for all cases. The break point was set based on tube hoop stress for a 0.050-inch thick wall at the maximum chamber pressure.

- The minimum tube width was 0.070 in.

For the parametric study, the code was used to calculate chamber wall temperature and heat flux distribution, tube hoop stress, coolant heat pickup, and pressure loss for use in the performance evaluation.

C. CYCLE ANALYSIS

Heat transfer data, generated during the thermal analysis for the copper tube chamber, were correlated through regression analysis and incorporated into the expander engine cycle deck. Cycle data were generated for both the split and full expander engines, and an optimization was conducted to determine the chamber geometry with the maximum cycle chamber pressure. This geometry was subsequently reentered into the engine design deck to ensure that none of the turbomachinery or chamber limits had been exceeded and to obtain the final cycle parameter values.

1. Thermal Data

The heat transfer data generated for each point in the chamber thermal analysis Central Composite Design (CCD) matrix (Figures 4, 5, and 6) were regression fit into suitable form for incorporation into the expander cycle design deck. The seven independent variables (Table 5) were used during the regression procedure to approximate the copper tubular chamber heat transfer characteristics. As functions of these seven independent variables, relations for the following nine dependent engine design parameters were incorporated into the design deck:

- Total chamber pressure drop (DPT) — psi
- Maximum stress ratio (PRYS)
- Ultimate tube temperature margin (UTTM) — °R
- Total chamber heat pick up (QTOT) — Btu
- Inlet manifold pressure drop (DPIN) — psi
- Chamber pressure drop (DP) — psi
- Exit manifold pressure drop (DPEX) — psi
- Maximum hot-wall temperature (THOT) — °R
- Throat hot-wall temperature (UTTS) — °R

2. Expander Engine Design Cycle Deck

The expander engine design cycle deck was used to integrate the correlated heat transfer data and chamber limits with the cycle performance data and turbomachinery limits. With this computer model, calculations of flowrates, system pressures and temperatures, and turbopump horsepower requirements were made in an iterative manner until an energy balance for the system was achieved. The following design constraints were monitored to prevent specified state-of-the-art values from being exceeded.

- Turbine tip speeds must be less than 1900 ft/sec.
- Pump impeller tip speeds must be less than 2100 ft/sec.
- Ultimate tube temperature margin must be greater than 100°R.
- Maximum hot-wall temperature must be less than 1460°R.
- Throat hot-wall temperature must be less than 1460°R.
- Maximum stress ratio must be less than 90.0.

3. Split Expander Cycle Analysis

The appropriate CCD matrix was selected to generate a combination of cycle and chamber data for regression. For the split expander cycle, a six-variable matrix was chosen to conduct the cycle analysis. The matrix is presented in Figure 7. Values for independent parameters used are listed in Table 6.

		TPR	1.8									2.5									3.2								
		CR	2.5			3.5			5.0			2.5			3.5			5.0			2.5			3.5			5.0		
TN	WC	ASP / ZI	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20
80	3.5	1.0	○		●				●		○										●		○				○		●
		2.5																											
		4.0	●		○				○		●										○		●				●		○
	5.8	1.0																											
		2.5														●													
		4.0																											
	8.0	1.0	●		○				○		●										○		●				●		○
		2.5																											
		4.0	○		●				●		○										●		○				○		●
100	3.5	1.0																											
		2.5														●													
		4.0																											
	5.8	1.0														●													
		2.5					●						●		●	●	●		●						●				
		4.0														●													
	8.0	1.0																											
		2.5														●													
		4.0																											
120	3.5	1.0	●		○				○		●										○		●				●		○
		2.5																											
		4.0	○		●				●		○										●		○				○		●
	5.8	1.0																											
		2.5														●													
		4.0																											
	8.0	1.8	○		●				●		○										●		○				○		●
		2.5																											
		4.0	●		○				○		●										○		●				●		○

Figure 7. Split Expander Chamber Optimization

TABLE 6. — SPLIT EXPANDER CYCLE INDEPENDENT PARAMETERS

Turbine Pressure Ratio (TPR)	1.8	2.5	3.2
Contraction Ratio (CR)	2.5	3.5	5.0
Chamber Length (ZI) — in.	12.0	16.0	20.0
Tube Number (TN)	80	100	120
Flow Rate (WC) — lb/sec	3.5	5.8	8.0
Aspect Ratio (ASP)	1.0	2.5	4.0

Note that turbine pressure ratio was substituted in the cycle CCD matrix for chamber pressure as an independent variable so that chamber pressure could later be optimized as a function of TPR, CR, ZI, TN, and ASP. An aspect ratio of 1.8 was substituted for 1.0 in the case of the 120 tube number rows and flowrate (WC) = 8.0 (Figure 7) because of convergence requirements in the cycle deck encountered during the generation of the cycle data. This change does not affect the validity of the regression procedure.

After engine design data were generated for the 77 split expander cycle points, the regression routine was used to approximate the following variables:

- Chamber pressure (PC) — psi
- Fuel turbine tip speed (UMFT1) — ft/sec
- Oxygen turbine tip speed (UMOT1) — ft/sec
- Percent jacket bypass flow (WJBY)
- Chamber ultimate tube temperature (UTTM) — °R
- Chamber maximum hot-wall temperature (THOT) — °R
- Chamber throat hot-wall temperature (UTTS) — °R
- Chamber maximum stress ratio (PRYS).

Relations for these eight parameters were entered into an optimization deck to maximize chamber pressure at a specific jacket bypass flow. An optimum combination of TPR, CR, XI, ASP, and TN was found using the constraints listed in Paragraph II.C.2. These parameters were then input into the split expander cycle design deck to ensure their validity and obtain the final values for the independent variables (i.e., PC, UTTM).

4. Full Expander Cycle Analysis

The CCD matrix used to conduct the full expander with regenerator cycle analysis is shown in Figure 8. The six independent variables used are listed in Table 7.

TABLE 7. — FULL-EXPANDER INDEPENDENT PARAMETERS

Turbine Pressure Ratio (TPR)	1.8	2.5	3.2
Contraction Ratio (CR)	2.5	3.5	5.0
Chamber Length (ZI) — in.	12.0	16.0	20.0
Tube Number (TN)	80	100	120
Jacket Inlet Temperature (TIN) –°R	110.0	250.0	400.0
Aspect Ratio (ASP)	1.0	2.5	4.0

TPR	1.8									2.5									3.2											
CR	2.5			3.5			5.0			2.5			3.5			5.0			2.5			3.5			5.0			ASP	TC	TN
ZI	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20	12	16	20			
	○		●				●		○										●		○				○		●	1.0	110	80
																												2.5		
	●		○				○		●										○		●				●		○	4.0		
																												1.0	250	
														●														2.5		
																												4.0		
	●		○				○		●										○		●				●		○	1.0	400	
																												2.5		
	○		●				●		○										●		○				○		●	4.0		
																												1.0	110	100
														●														2.5		
																												4.0		
														●														1.0	250	
					●						●		●	●	●		●						●					2.5		
														●														4.0		
																												1.0	400	
														●														2.5		
																												4.0		
	●		○				○		●										○		●				●		○	1.0	110	120
																												2.5		
	○		●				●		○										●		○				○		●	4.0		
																												1.0	250	
														●														2.5		
																												4.0		
	○		●				●		○										●		○				○		●	1.8	400	
																												2.5		
	●		○				○		●										○		●				●		○	4.0		

Figure 8. Full Expander With Regenerator Chamber Optimization

As with the split expander cycle, an aspect ratio of 1.8 was substituted for 1.0 in one of the 120 tube number cases in the matrix (Figure 8) because of difficulty experienced in the convergence of certain points. In the case of the full expander, WC was replaced with TIN as a dependent variable, since there was no bypass flow.

Following the same procedure used for the split expander, the engine design for the full expander cycle with regenerator was regressed. From the regression routine, approximating relations were obtained for the following dependent variables:

- Chamber pressure (PC) - psi
- Fuel turbine tip speed (UMFT1) - ft/sec
- Oxygen turbine tip speed (UMOT1) - ft/sec
- Jacket Inlet Temperature (TIN) – °R
- Chamber ultimate tube temperature (UTTM) - °R
- Chamber maximum hot-wall temperature (THOT) - °R
- Chamber throat hot-wall temperature (UTTS) - °R
- Chamber maximum stress ratio (PRYS).

The optimization deck was again used to optimize PC, adhering to the cycle constraints listed in Paragraph II.C.2. After the optimum chamber geometry and turbine pressure ratio were found for a specified jacket inlet temperature, these parameters were input into the full expander with regenerator cycle design deck to ensure their validity and obtain the final values for the dependent variables.

SECTION III
THERMAL ANALYSIS AND SENSITIVITY STUDY RESULTS

A. SPLIT EXPANDER CYCLE OPTIMIZATION

Using the optimization procedure described in Section II, an optimum thrust chamber pressure of 1755 psia was achieved for the split expander cycle. This represents a 195 psi (11 percent) increase over a comparable cycle with a milled channel chamber (Reference 1). With this cycle (Figure 9), hot-wall temperature near the injectors and fuel pump tip speed are the critical factors limiting further chamber pressure increase. As discussed later in this section, the limitation of tip speed on chamber pressure can be overcome through use of a four-stage fuel pump. The sensitivity of the cycle and chamber to perturbations around the optimum point is shown in Figures 10 through 12. The optimum configuration for maximum chamber pressure for the split expander cycle is presented in Table 8.

TABLE 8. — SPLIT EXPANDER OPTIMUM CONFIGURATION

• Chamber Contraction Ratio	—	3.0
• Tube Aspect Ratio (ASP)	—	3.0
• Tube Number (TN)	—	120
• Chamber Length — in.	—	15.25

B. FULL EXPANDER WITH REGENERATOR CYCLE OPTIMIZATION

The optimum thrust chamber configuration with a regenerator cycle produces a chamber pressure of 2150 psia, assuming 28-percent regenerator effectiveness. This represents a 433 psi increase (25 percent) over a comparable cycle with a milled channel chamber (Reference 2). With this cycle (Figure 13), the minimum ultimate tube temperature margin is the critical factor limiting further chamber pressure increase. The sensitivity of the cycle and chamber to perturbations around the optimum point is presented in Figures 14 through 16. The optimum chamber configuration to maximize chamber pressure for the full expander with regenerator cycle is presented in Table 9.

TABLE 9. — FULL EXPANDER OPTIMUM CHAMBER CONFIGURATION

• Chamber Contraction Ratio (R)	—	3.4
• Tube Aspect Ratio (ASP)	—	3.0
• Tube Number (TN)	—	100
• Chamber Length — in.	—	18.0

C. VARIATION STUDIES

Following the optimization of the basic (18-percent tube enhancement) split expander and full expander with regenerator cycles, a study was initiated to examine further refinements to the cycles to achieve additional cycle improvements. These involved the following:

- Increasing assumed heat flux enhancement from the tubular geometry
- Increasing jacket bypass flow
- Increasing the number of chamber tubes (decreasing minimum tube diameter)
- Optimizing chamber tube geometry (constant wall temperature)
- Increasing the maximum allowable chamber hot-wall temperature
- Using a four-stage fuel pump.

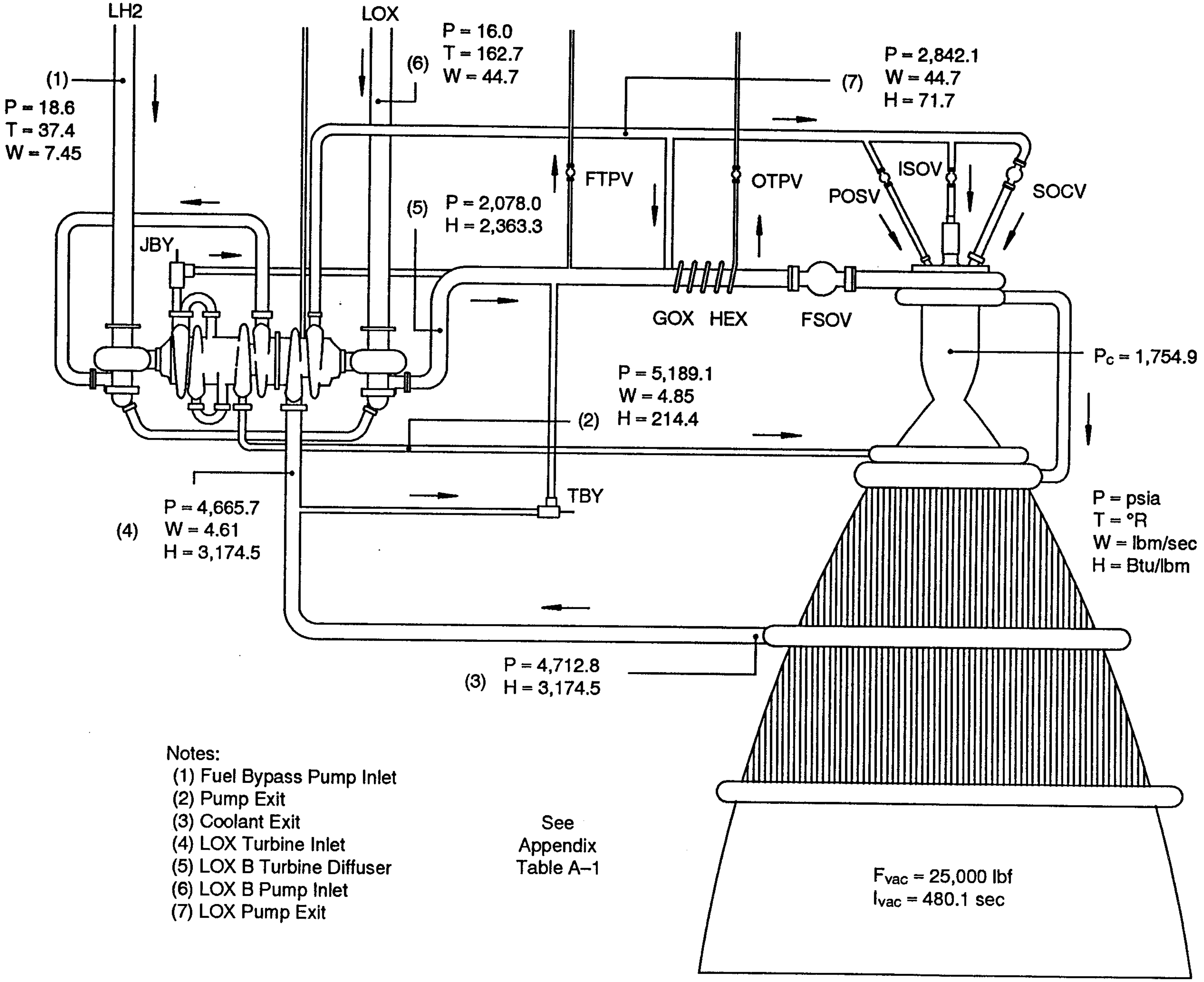


Figure 9. Optimized Split Expander

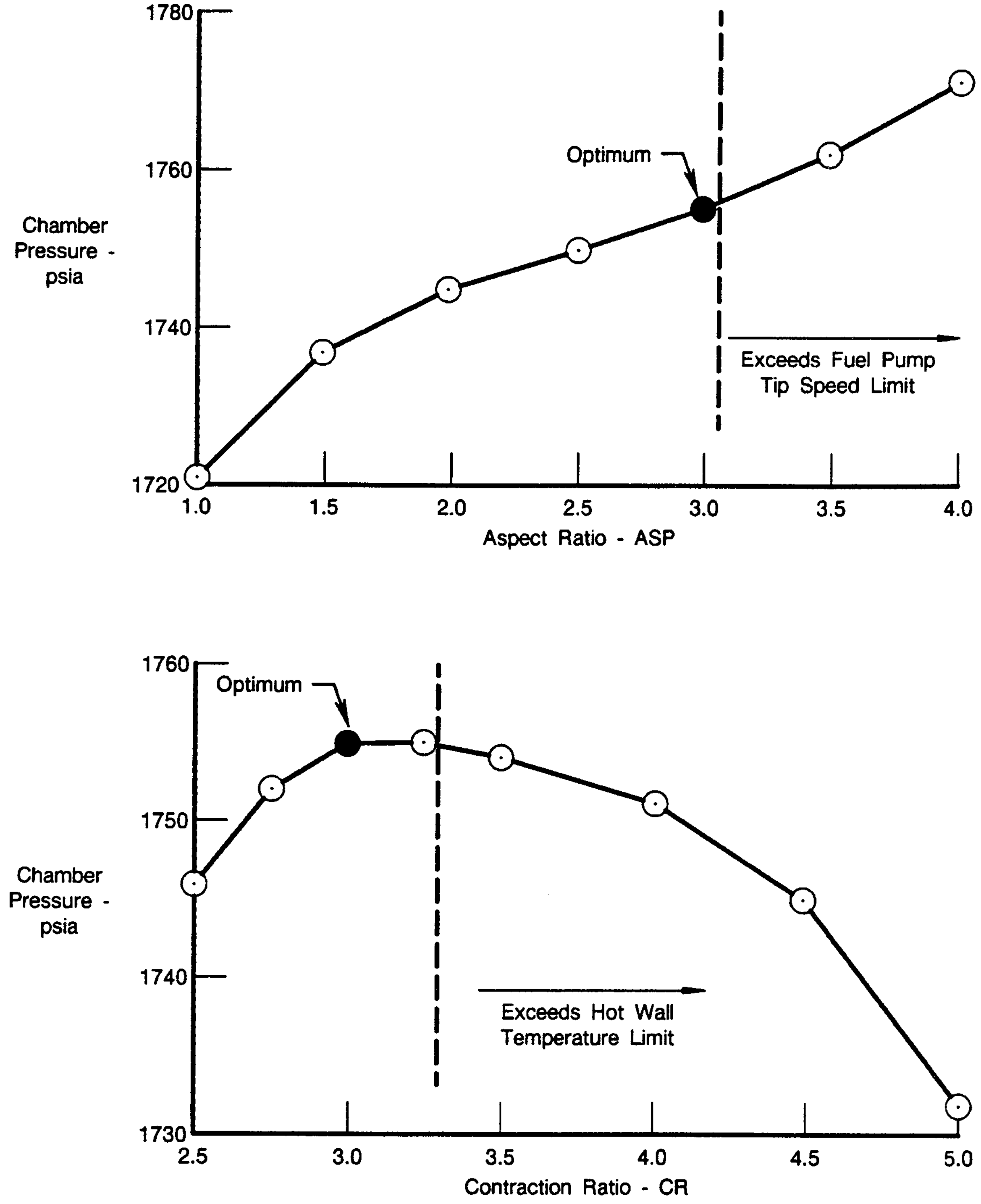


Figure 10. Effect of Tube Aspect Ratio and Chamber Contraction Ratio on Achievable Chamber Pressure — Split Expander Cycle

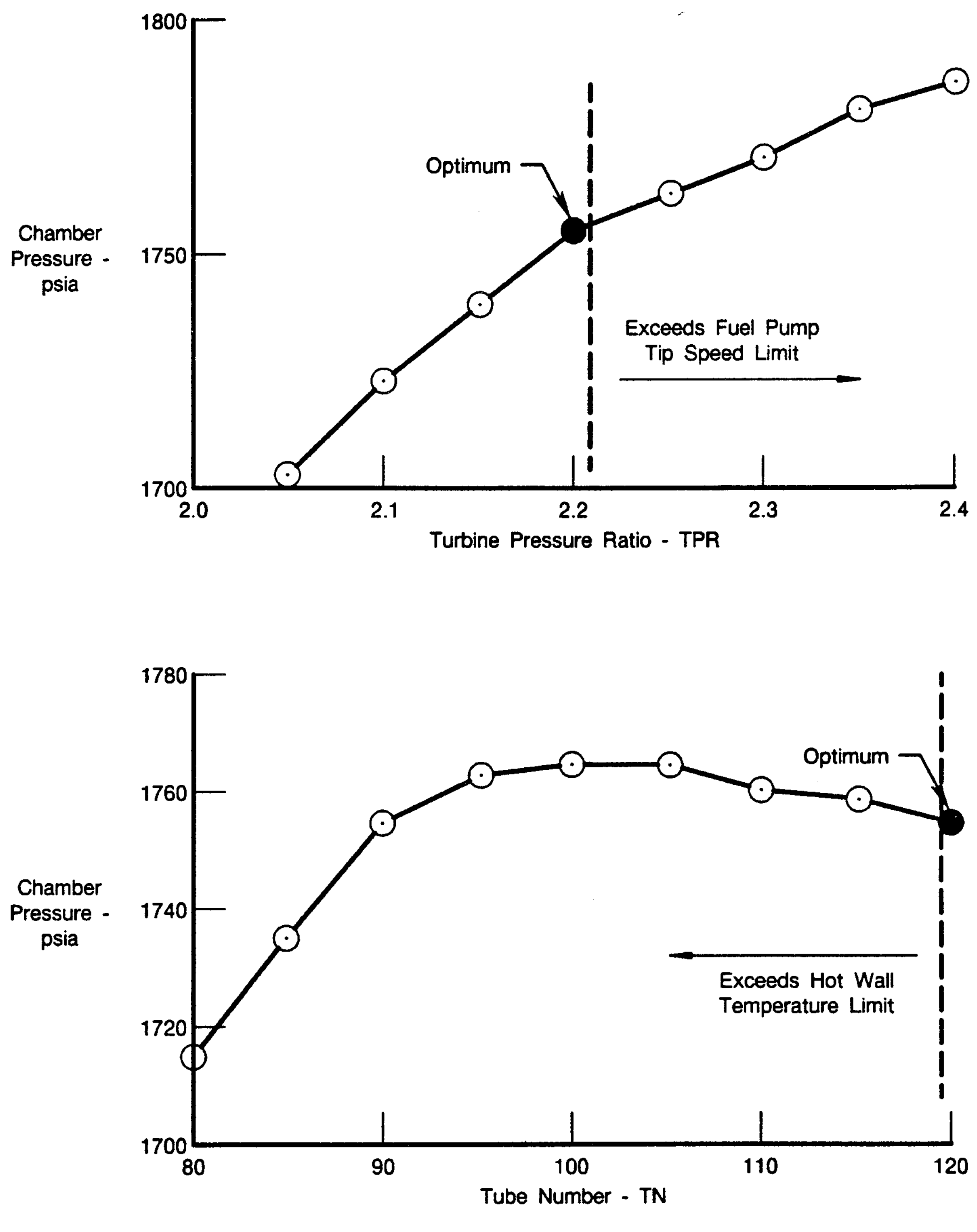
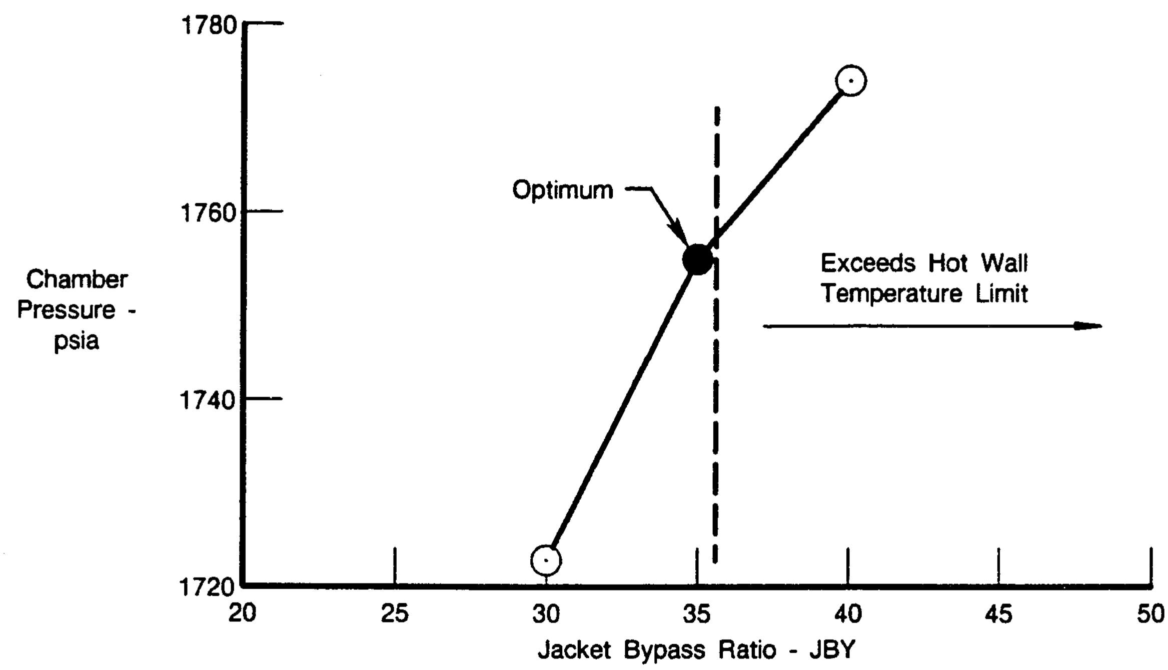


Figure 11. Effect of Turbine Pressure Ratio and Number of Tubes on Achievable Chamber Pressure — Split Expander Cycle



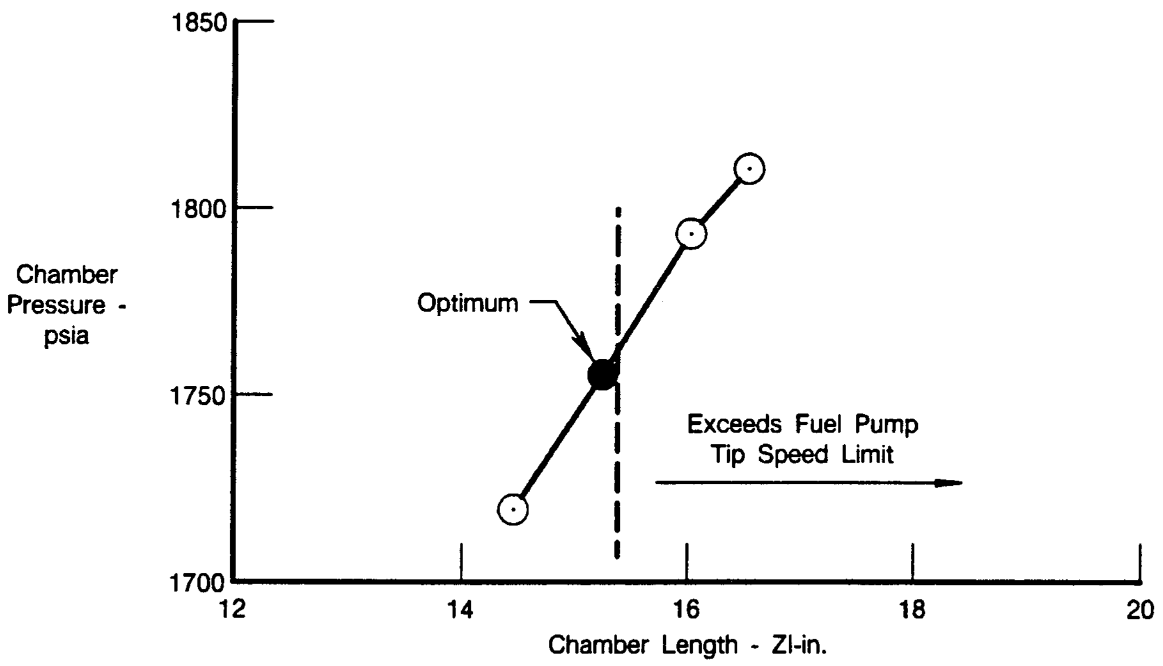


Figure 12. Effect of Turbine Bypass Ratio and Chamber Length on Achievable Chamber Pressure — Split Expander Cycle

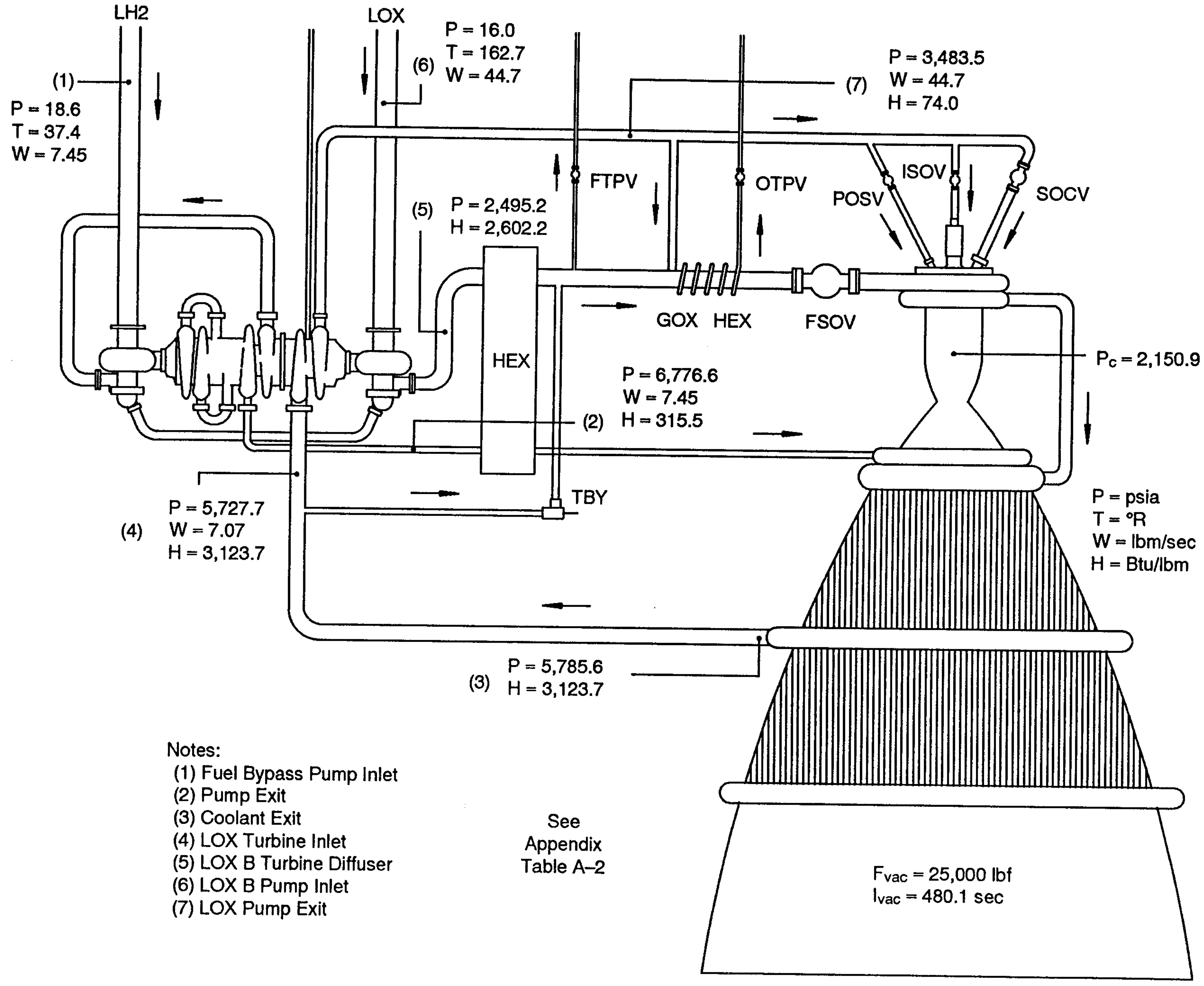


Figure 13. Optimized Full Expander With Regenerator

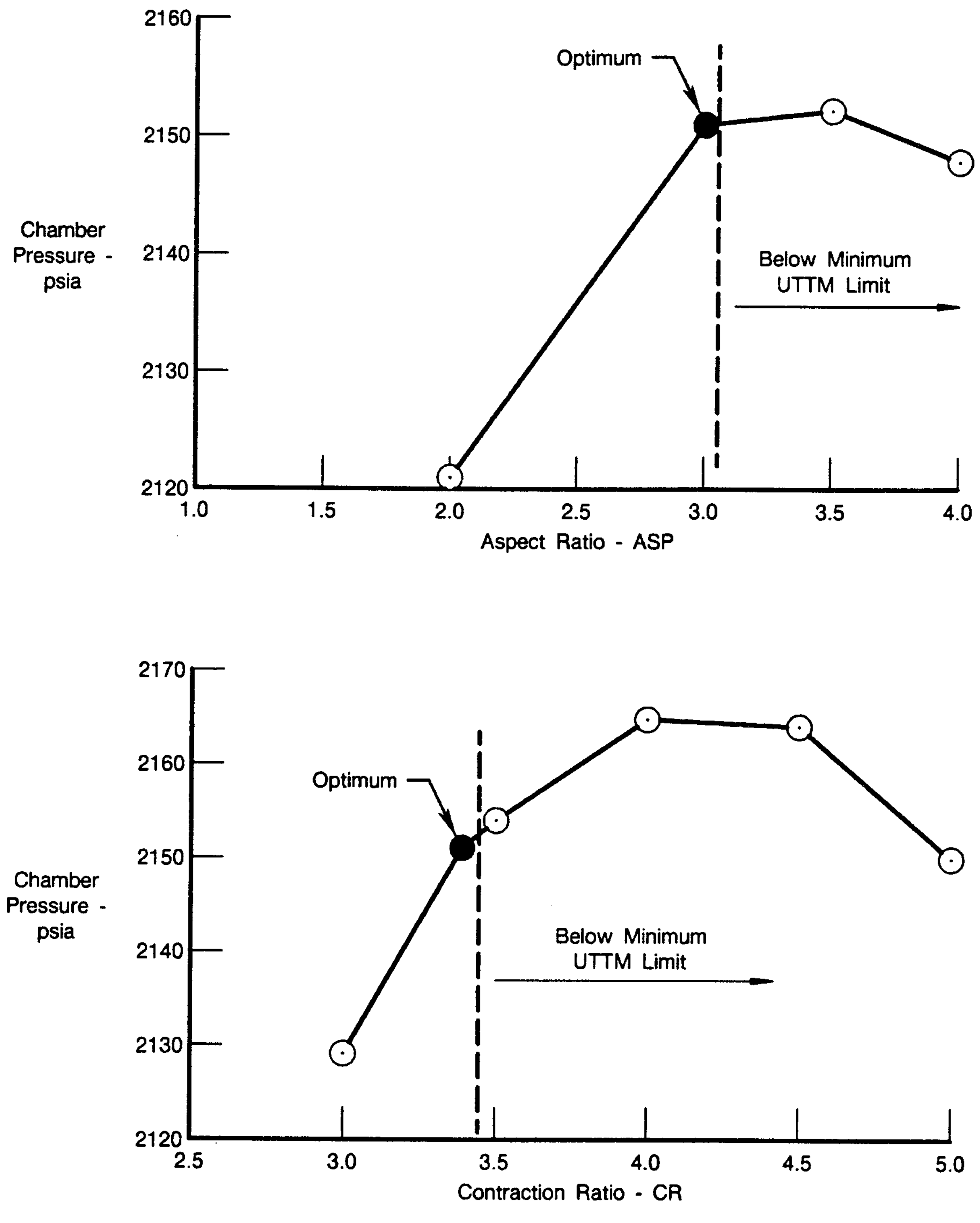


Figure 14. Effect of Aspect Ratio and Contraction Ratio on Achievable Chamber Pressure — Full Expander Cycle with Regenerator

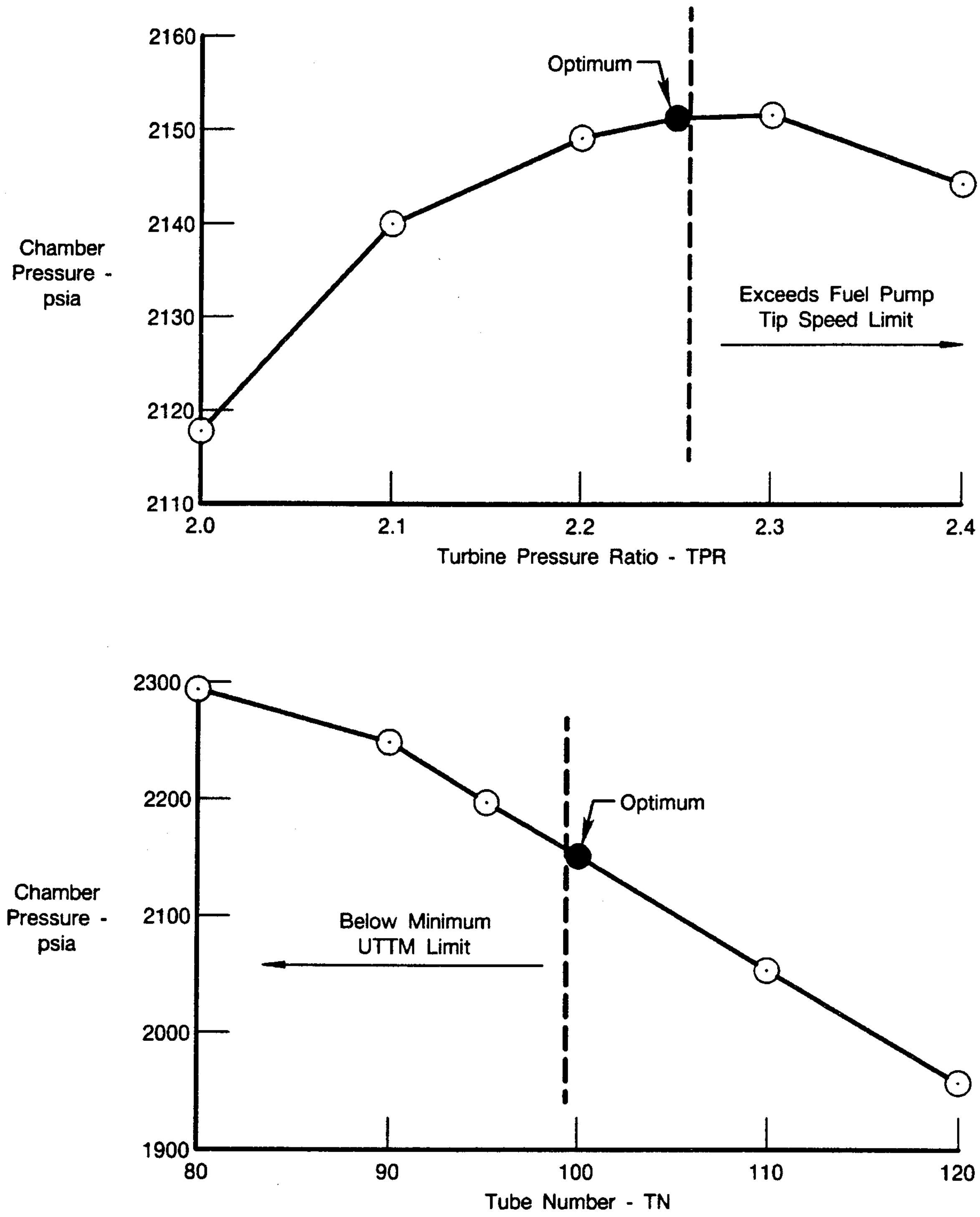


Figure 15. Effect of Turbine Pressure Ratio and Number of Tubes on Achievable Chamber Pressure — Full Expander Cycle with Regenerator

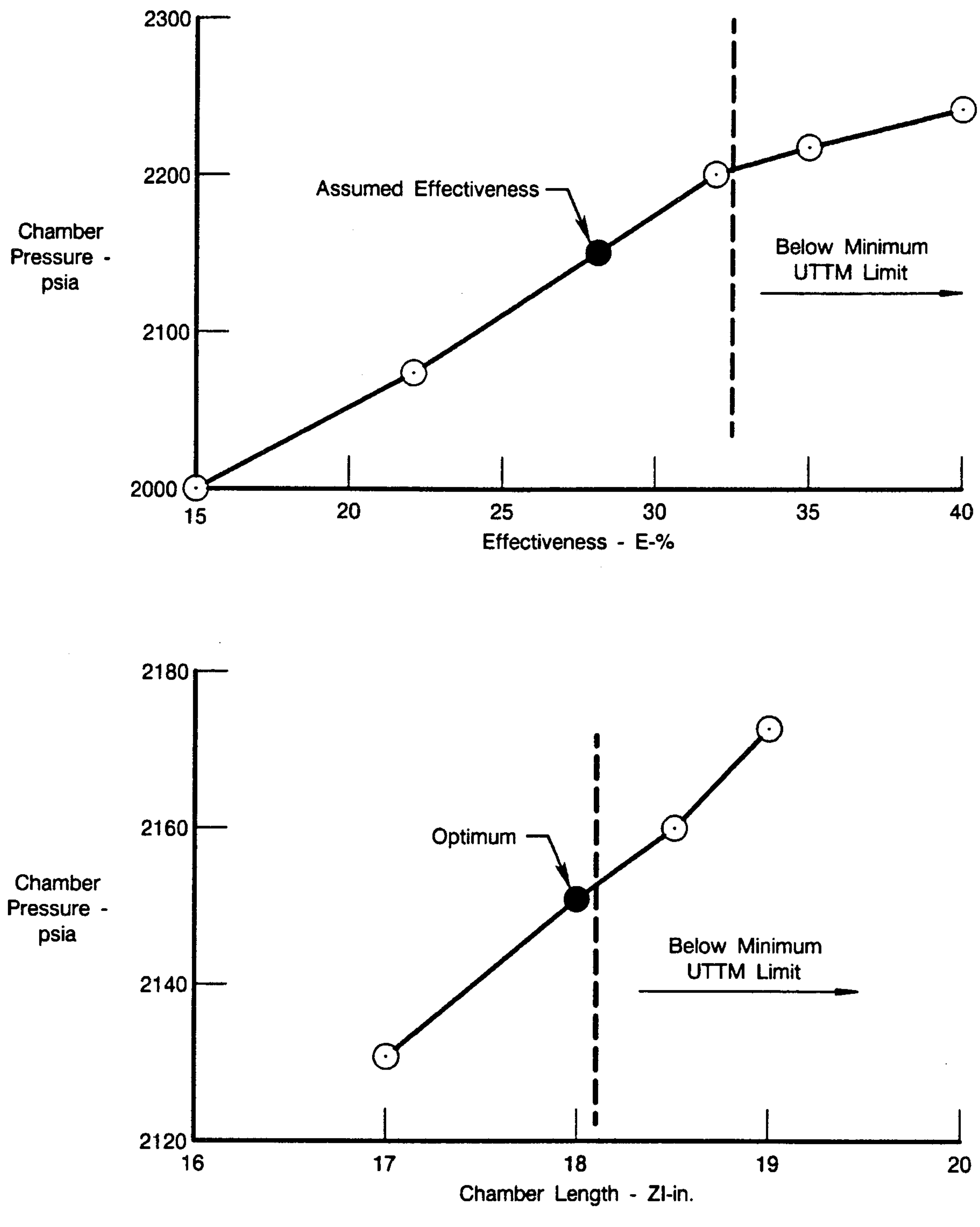


Figure 16. Effect of Regenerator Effectiveness and Chamber Length on Achievable Chamber Pressure — Full Expander Cycle with Regenerator

1. Increasing Heat Flux Enhancement

The effect of increasing the assumed chamber tube enhancement from 18 percent to 30 percent was studied for both the optimized split expander cycle and the full expander with regenerator cycle. The optimized split expander cycle with 30-percent enhanced heat transfer

provides an increase in total heat flux to the chamber that is available for providing increased cycle chamber pressure. However, increasing enhancement without increasing the number of fuel pump stages tends to drive the fuel pump tip speed over the allowable limit (2100 ft/sec), forcing a reduction in turbine pressure ratio. Because the fuel pump tip speed was near the limit, the increase in chamber pressure realized as a result of increased enhancement was negligible. The final 35-percent jacket bypass split expander cycle with a chamber pressure of 1758 psia using the 30-percent enhanced heat transfer is presented in Figure 17.

Similarly, no improvement from the optimized base (18-percent tube enhancement) cycle was gained with the assumption of the 30-percent enhanced tubes for the full expander with regenerator cycle. The printout for the full expander with regenerator, 30-percent enhanced cycle is presented in Figure 18.

2. Increasing Jacket Bypass Flow

Although the effect of increased enhancement was negligible on the optimized 35-percent jacket bypass flow split expander cycle, enhancement can have significant effect at higher jacket bypass ratios. At a jacket bypass ratio of 45 percent, for instance, a cycle using 18-percent enhancement will only reach a chamber pressure level of 1640 psia before exceeding chamber hot-wall temperature limits. However, with 30-percent enhanced heat transfer, the maximum chamber pressure attainable with the 50-percent jacket bypass ratio cycle is 1756. psia (at the fuel pump tip speed limit), as shown in the cycle printout in Figure 19. An increased jacket bypass ratio cycle is possible when the increased chamber tube enhancement is assumed. The effect of increasing the bypass ratio is shown in Figure 20 for both the 18-percent and 30-percent enhanced tube configurations. As discussed in Reference 2, a high jacket bypass flow is desirable for providing cooling margin for throttling and high mixture ratio operation.

3. Increasing the Number of Tubes

The effect of increasing the number of chamber tubes (decreasing the minimum tube diameter) was analyzed for the split expander cycle with 50-percent bypass flow and 30-percent heat transfer enhancement. The effect on the chamber was a decrease in both chamber pressure loss and heat transfer. Although the cycle in Figure 21 showed a reduction in fuel pump exit pressure from 5350. to 5296. psia, the overall effect on chamber pressure from increasing the number of tubes was negligible because of fuel tip speed limits.

4. Optimizing Chamber Tube Geometry

To minimize coolant pressure drop in the chamber, the tube wall perimeter was varied to allow the wall temperature to attain its maximum temperature of 1460°R over its entire length. This chamber tube configuration resulted in the most favorable tradeoff between coolant heat flux and pressure drop. Incorporation of the optimum geometry into the 50-percent bypass flow, 30-percent enhanced split expander cycle (Figure 22) resulted in a pump exit pressure decrease of 57 psia (compare Figures 21 and 22). Chamber pressure, however, remained unaffected by the optimized tube geometry, since the cycle is operating on the 1st-stage fuel pump tip speed limit. Further significant increases in chamber pressure for the split expander cycle above the 1755 psia level appears possible only with the use of a fourth fuel pump stage to reduce tip speed.

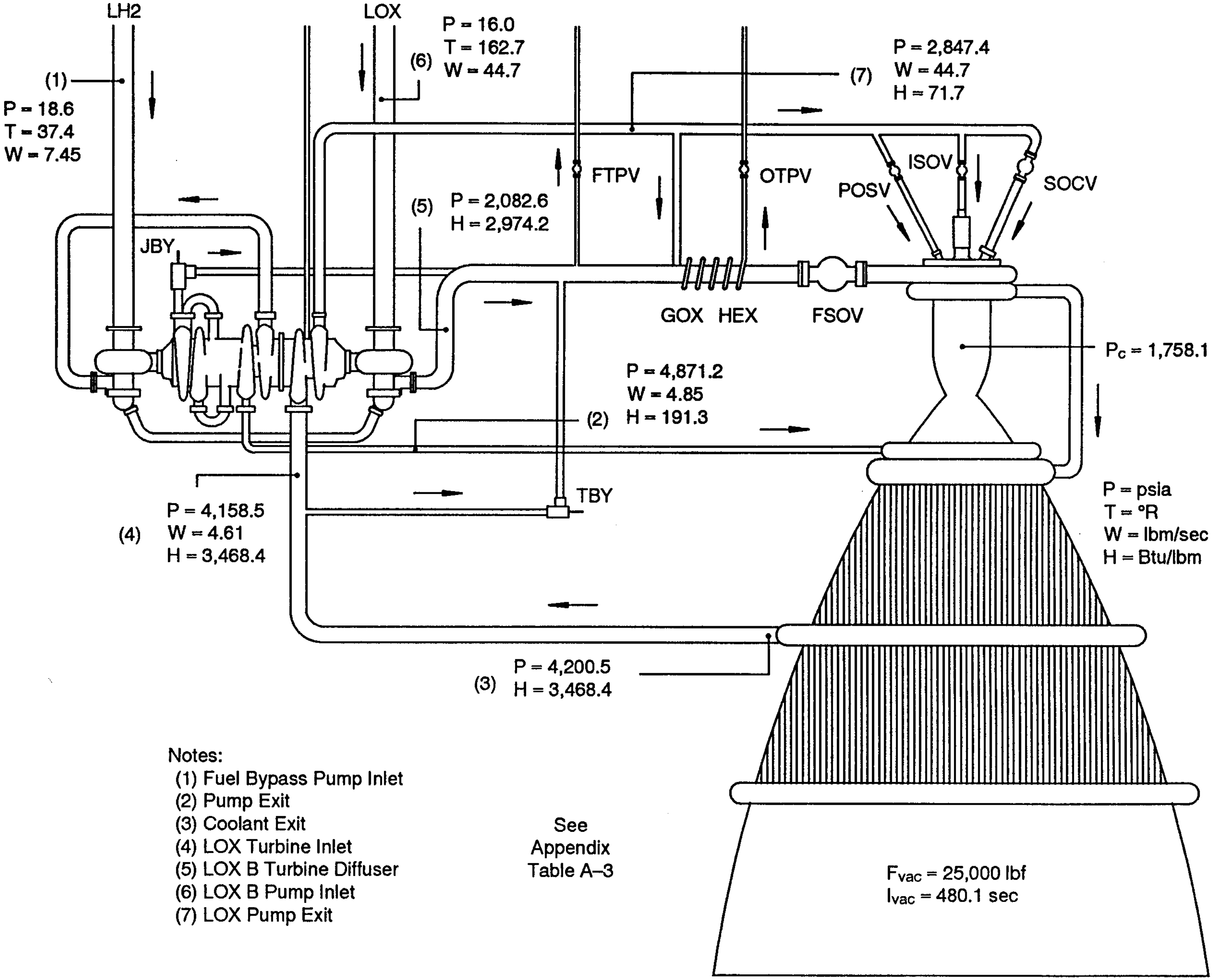


Figure 17. Split Expander — 35-Percent Jacket Bypass/30-Percent Enhancement

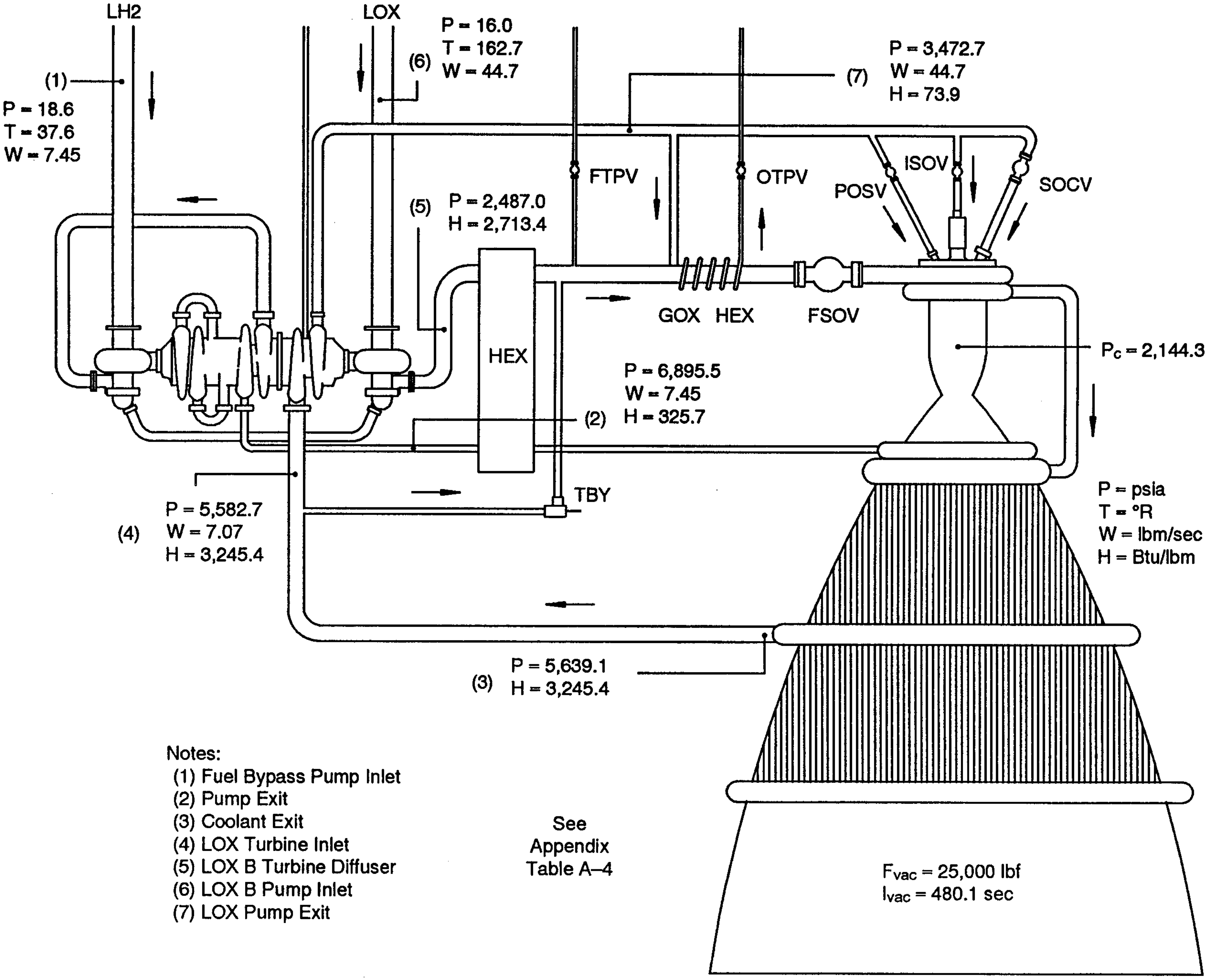


Figure 18. Full Expander with Regenerator — 30-Percent Enhancement

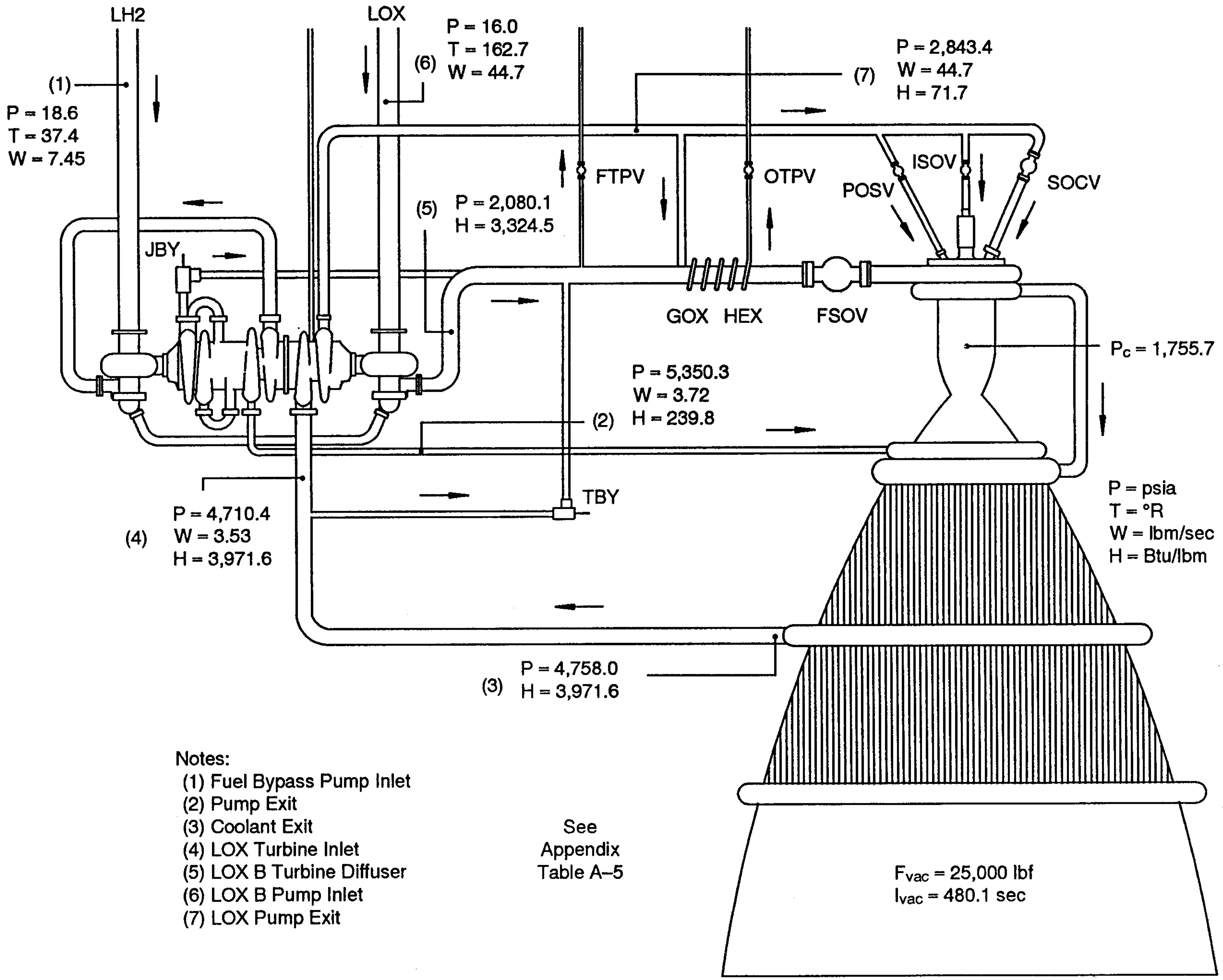


Figure 19. Split Expander — 50-Percent Jacket Bypass/30-Percent Enhancement

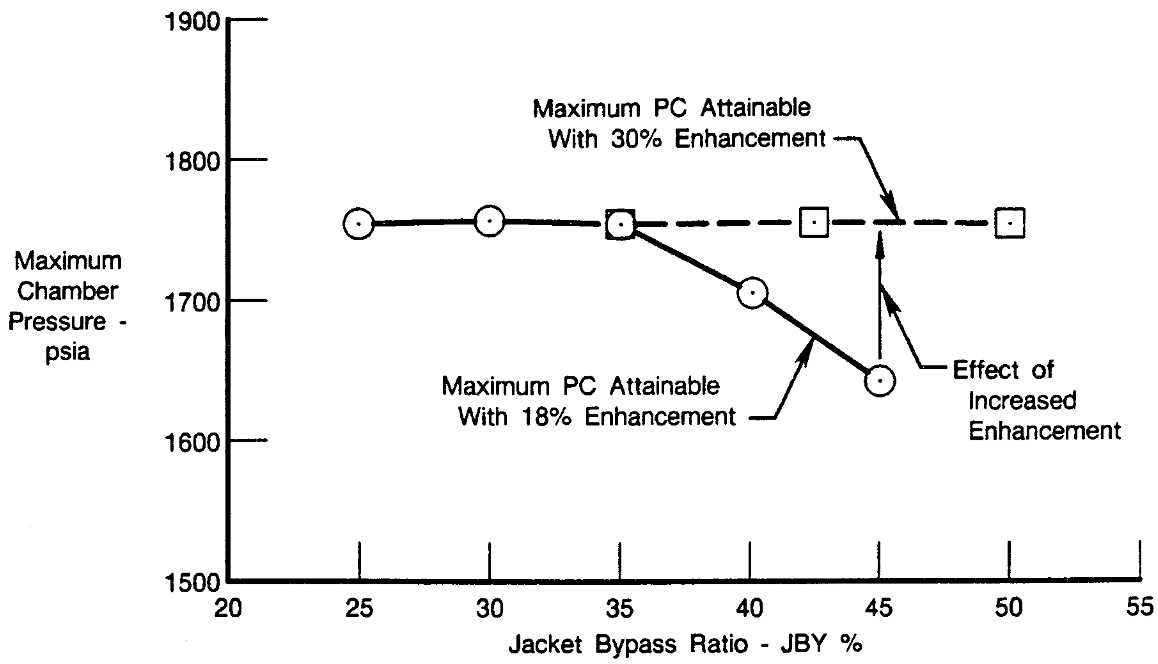


Figure 20. Effect of Jacket Bypass Flow on Achievable Chamber Pressure — Split Expander Cycle

5. Increasing the Maximum Allowable Chamber Hot-Wall Temperature

The effect of increasing the allowable thrust chamber hot-wall temperature on upper limit chamber pressure was investigated for the split expander cycle with 50-percent bypass flow (i.e., the configuration that was not fuel pump tip speed limited). By raising the maximum wall and 18 percent enhancement (i.e., the configuration that was not fuel pump tip speed limited). By raising the maximum wall temperature to 1560°R, a chamber pressure of 1701 psia is achieved (Figure 23). Note that this cycle is also operating on the minimum ultimate tube temperature margin (UTTM) limit of 100°R. If the maximum wall temperature limit is raised to 1660°R and the UTTM limit is disregarded, the maximum chamber pressure is 1757 psia, as shown in Figure 24 (this cycle is operating on the pump tip speed limit).

6. Using A Four-Stage Pump

The preceding analyses showed that the maximum attainable chamber pressure for the split expander cycle, regardless of bypass ratio or assumed chamber enhancement, was bounded in the 1750 to 1760 psia range. Higher pressures were prevented by the fuel pump tip speed limit.

The use of a four-stage fuel pump was examined in an effort to decrease the pump impeller tip speed and allow further chamber pressure increase. To accommodate the additional fuel pump stage, the configuration of the fuel turbopump was altered. Back-to-back counterrotating turbines were selected to power the split rotor, four-stage fuel pump. This configuration replaced the three-stage fuel pump powered by a single two-stage fuel turbine.

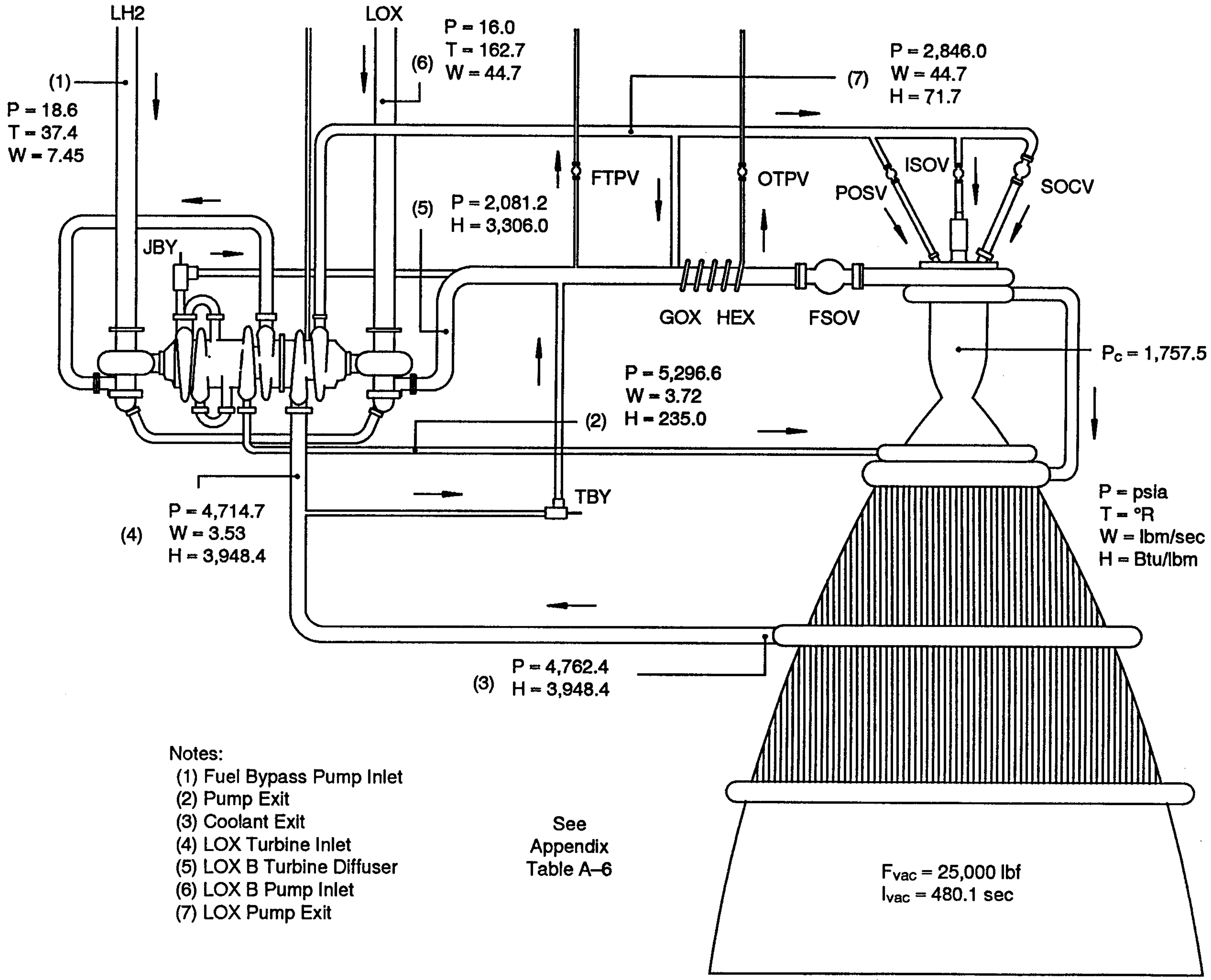


Figure 21. Split Expander — 50-Percent Jacket Bypass/30-Percent Enhancement — 150 Tubes

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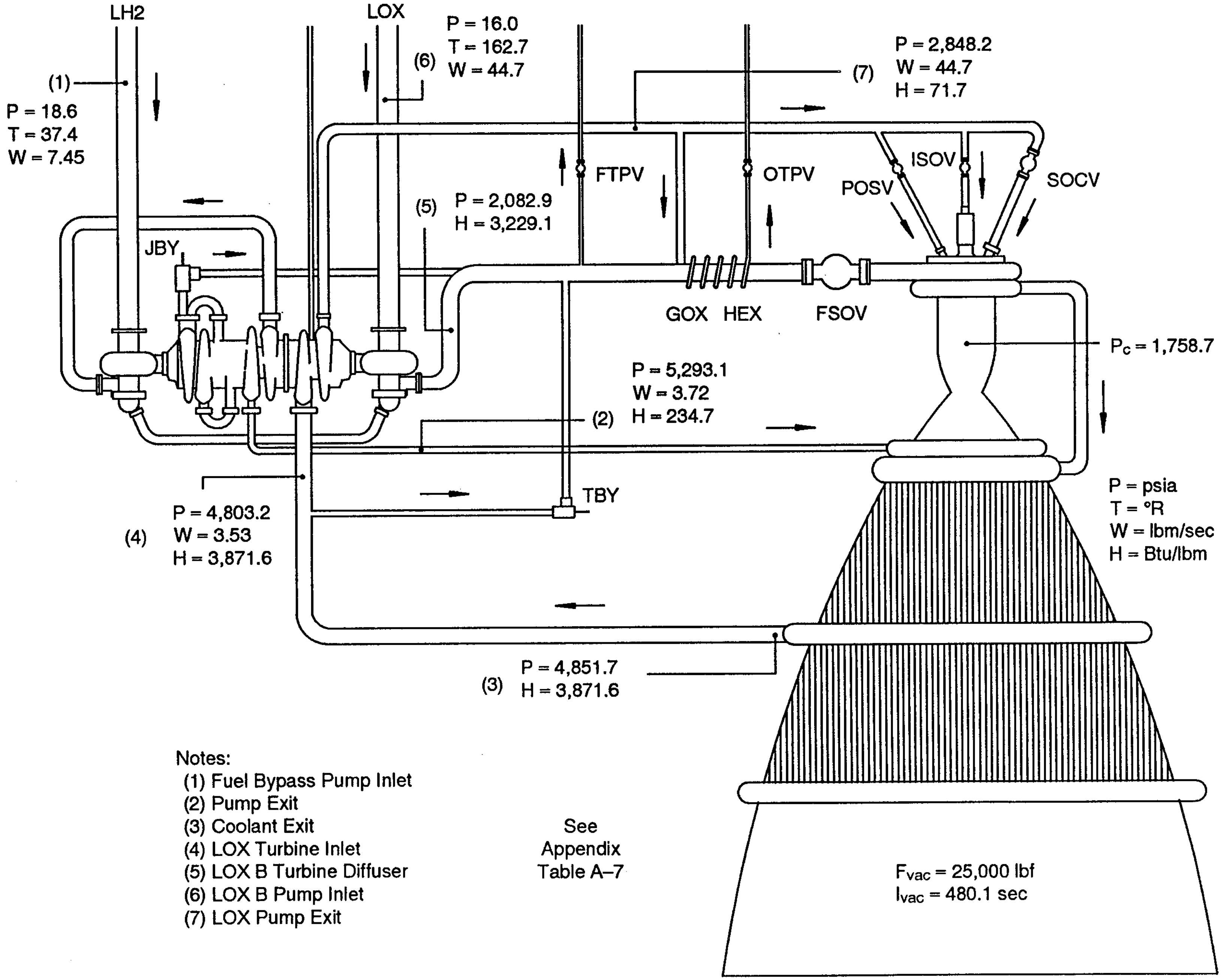

Figure 22. Split Expander — 50-Percent Jacket Bypass/30-Percent Enhancement — Optimum Tube Geometry

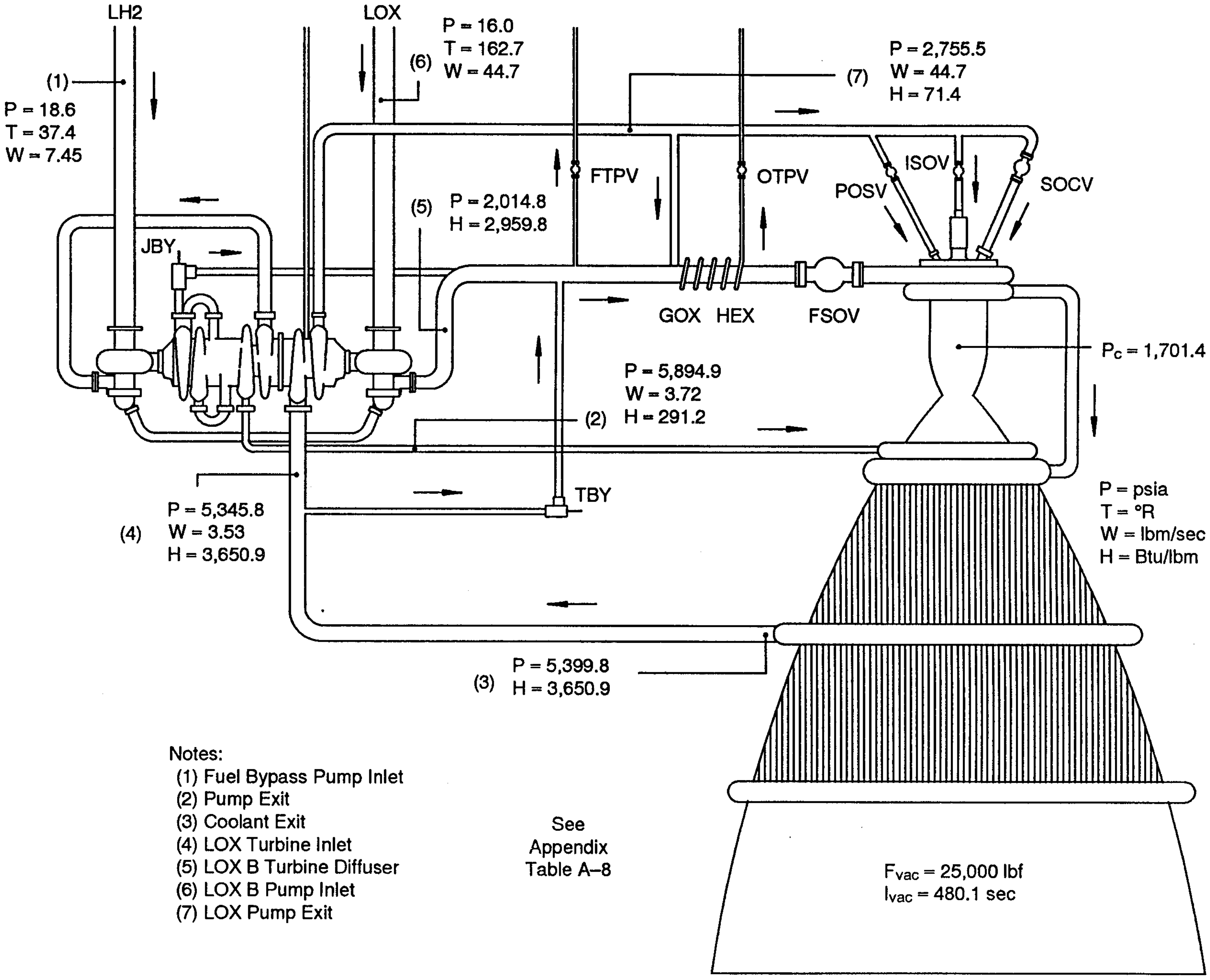

Figure 23. Split Expander — 1560°R Hot-Wall Temperature Limit

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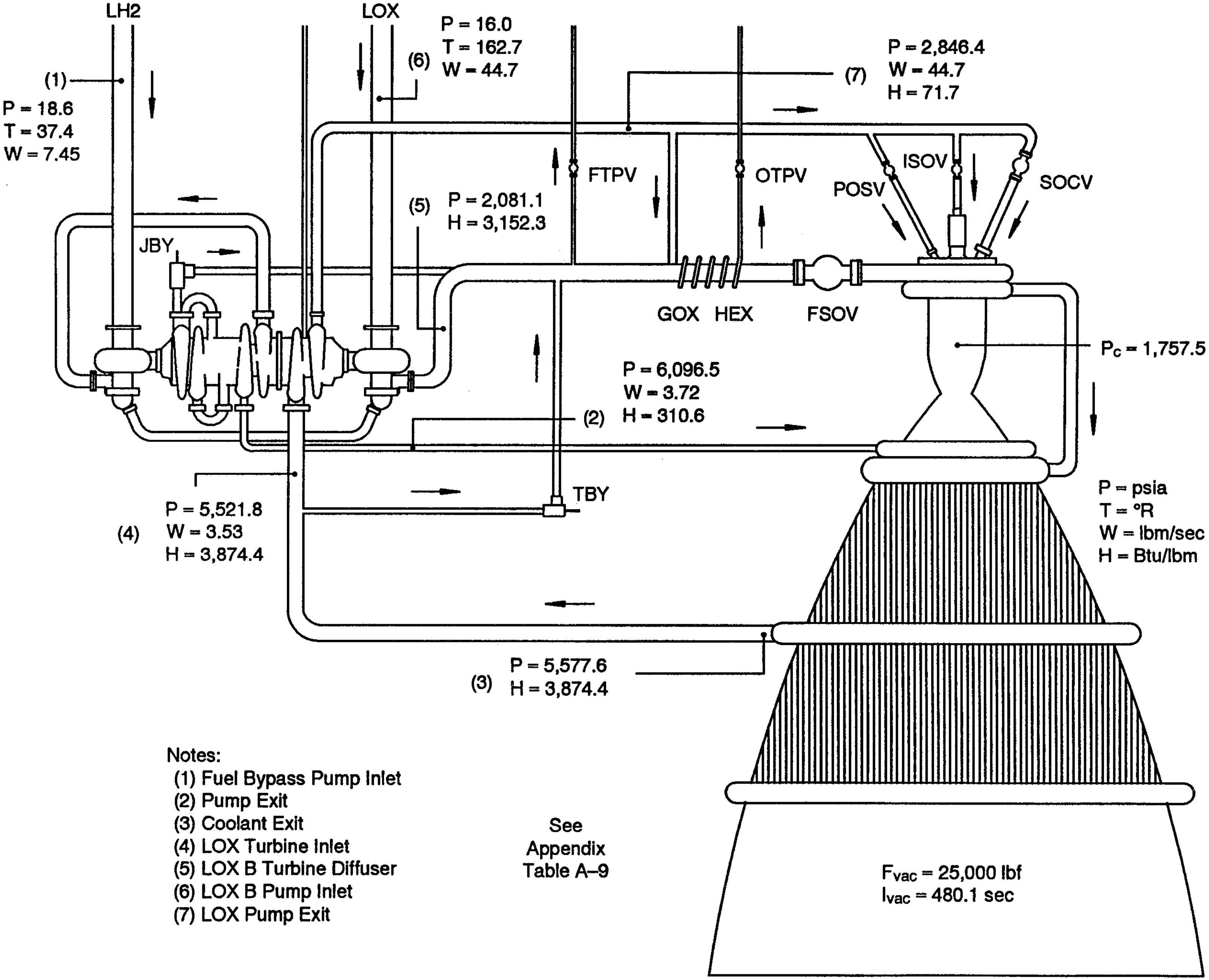


Figure 24. Split Expander — 1660°R Hot-Wall Temperature Limit

In addition to decreasing the tip speed, the four-stage fuel pump also improves pump efficiency. The higher pump efficiency provides increased pump exit pressure for an equivalent power input, providing potential for increased chamber pressure operation. Additional improvement is gained when a four-stage pump is used in a cycle previously limited by pump tip speed. The effect of the four-stage fuel pump on the split expander cycle is summarized and compared to previously optimized three-stage pump cycles in Table 10. The four-stage pump cycles are shown separately in Figures 25 through 28.

TABLE 10. — FOUR-STAGE FUEL PUMP EVALUATION (SPLIT EXPANDER ENGINE CYCLE)

Chamber Bypass (%)	*Chamber Enhancement (%)*	*Maximum Chamber Pressure (psia)*	
		3-Stage Pump	*4-Stage Pump*
35	18	1754.9	1922.2
35	30	1758.1	2049.6
50	18	1757.5*	1916.6*
50	30	1755.7	2161.7

Note:
*These cycles are operating with a chamber wall temperature limit of 1660 R.

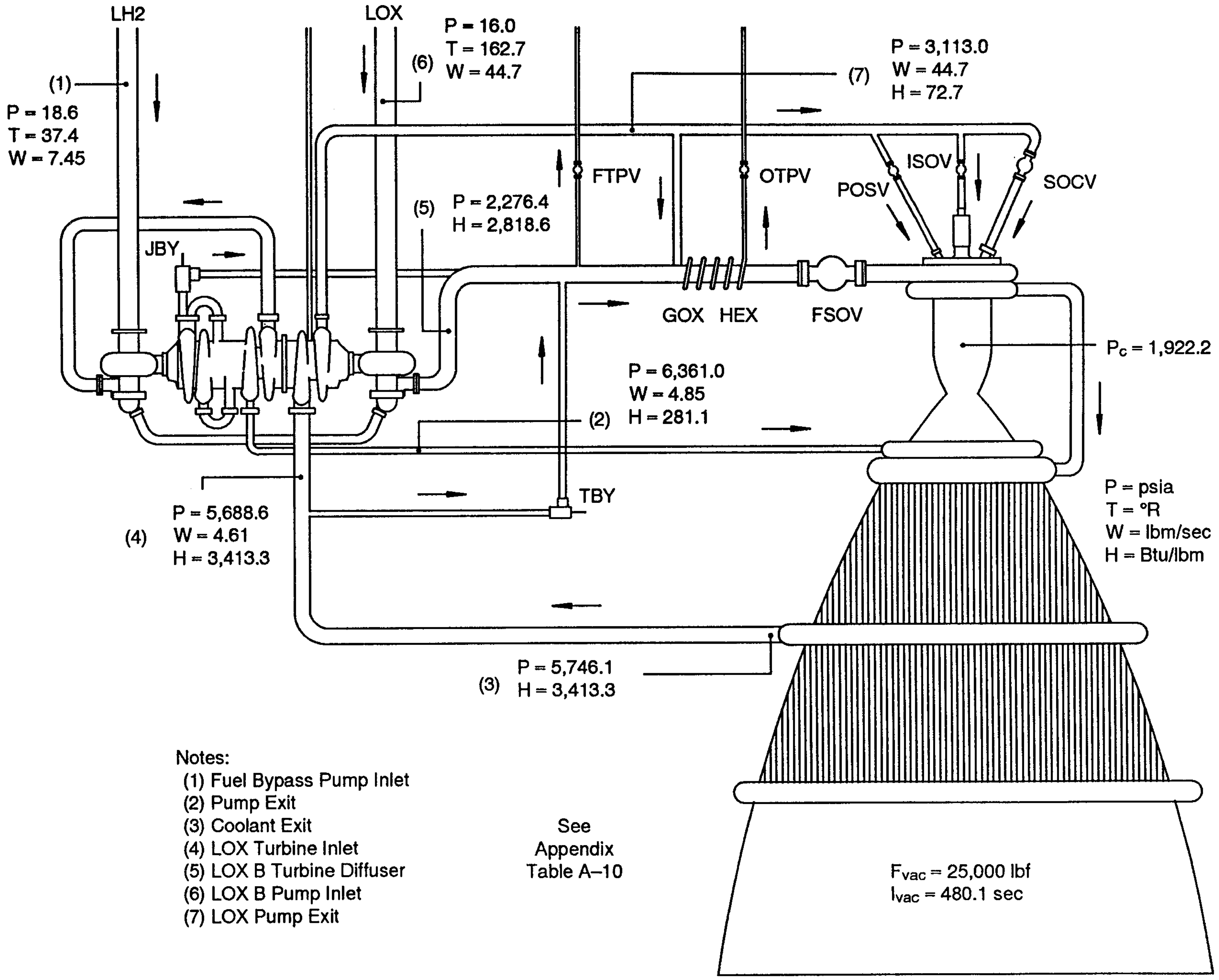


Figure 25. Split Expander — 35-Percent Bypass/18-Percent Enhancement — Four-Stage Pump

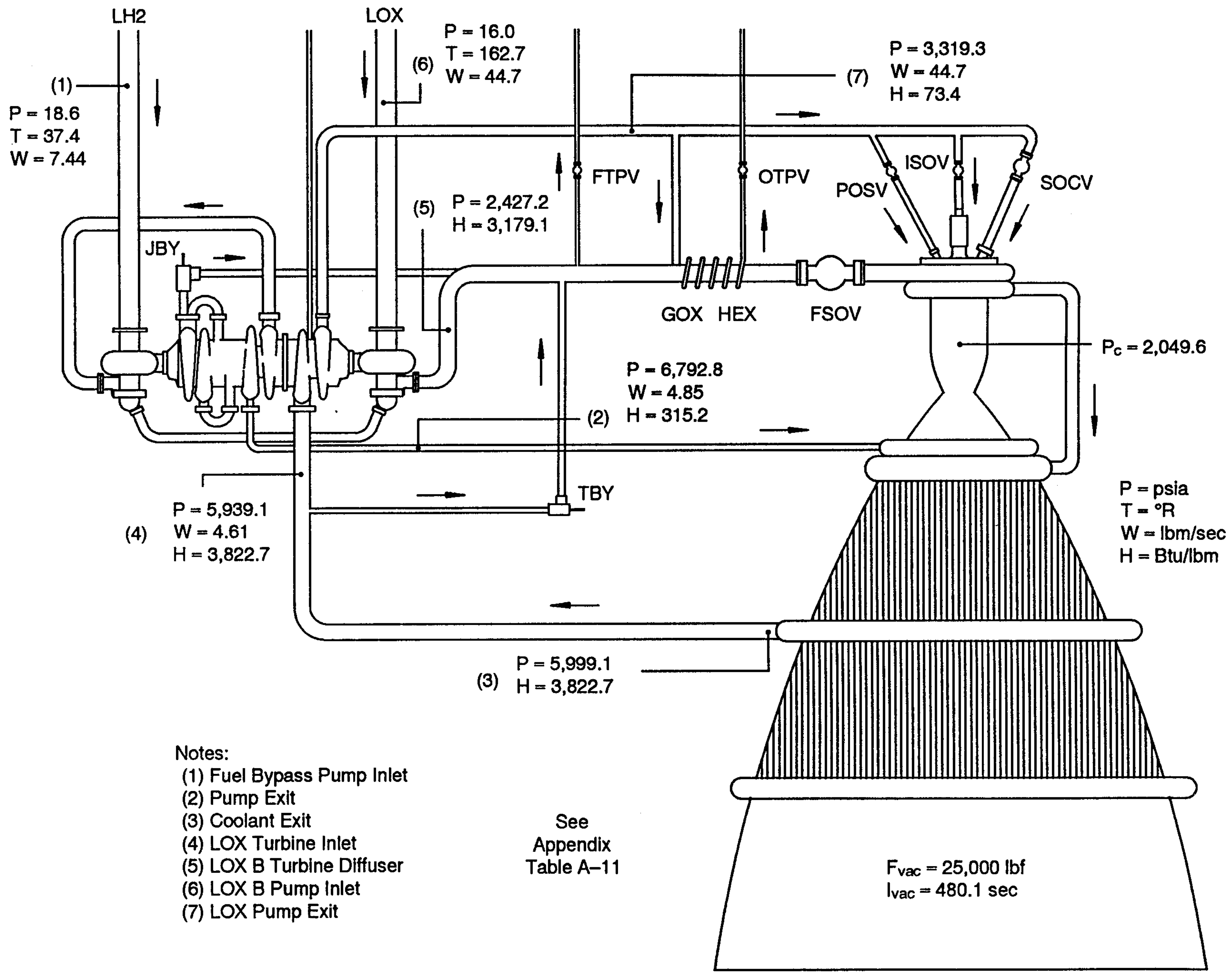


Figure 26. Split Expander — 35-Percent Bypass/30-Percent Enhancement — Four-Stage Pump

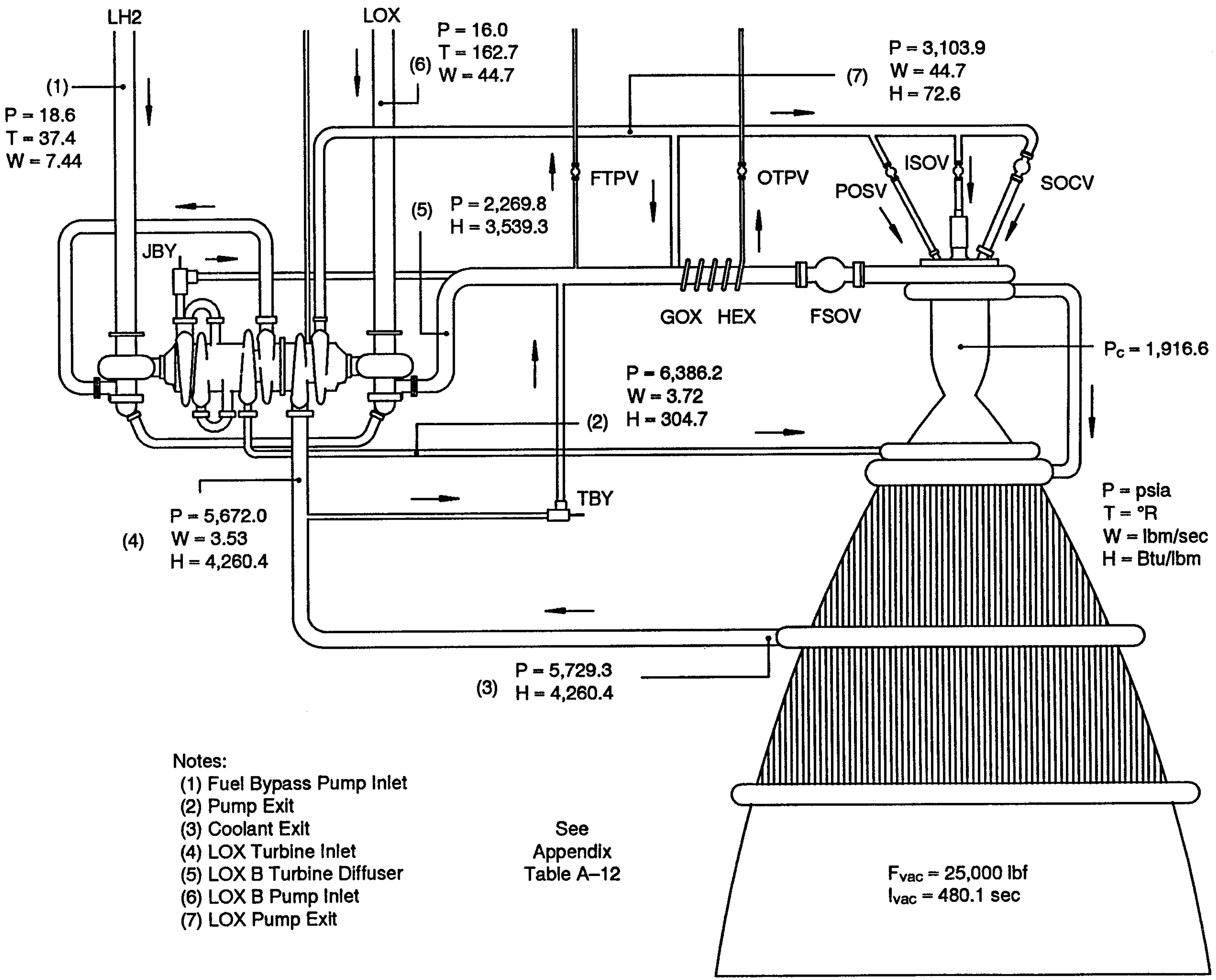


Figure 27. Split Expander — 50-Percent Bypass/18-Percent Enhancement — Four-Stage Pump

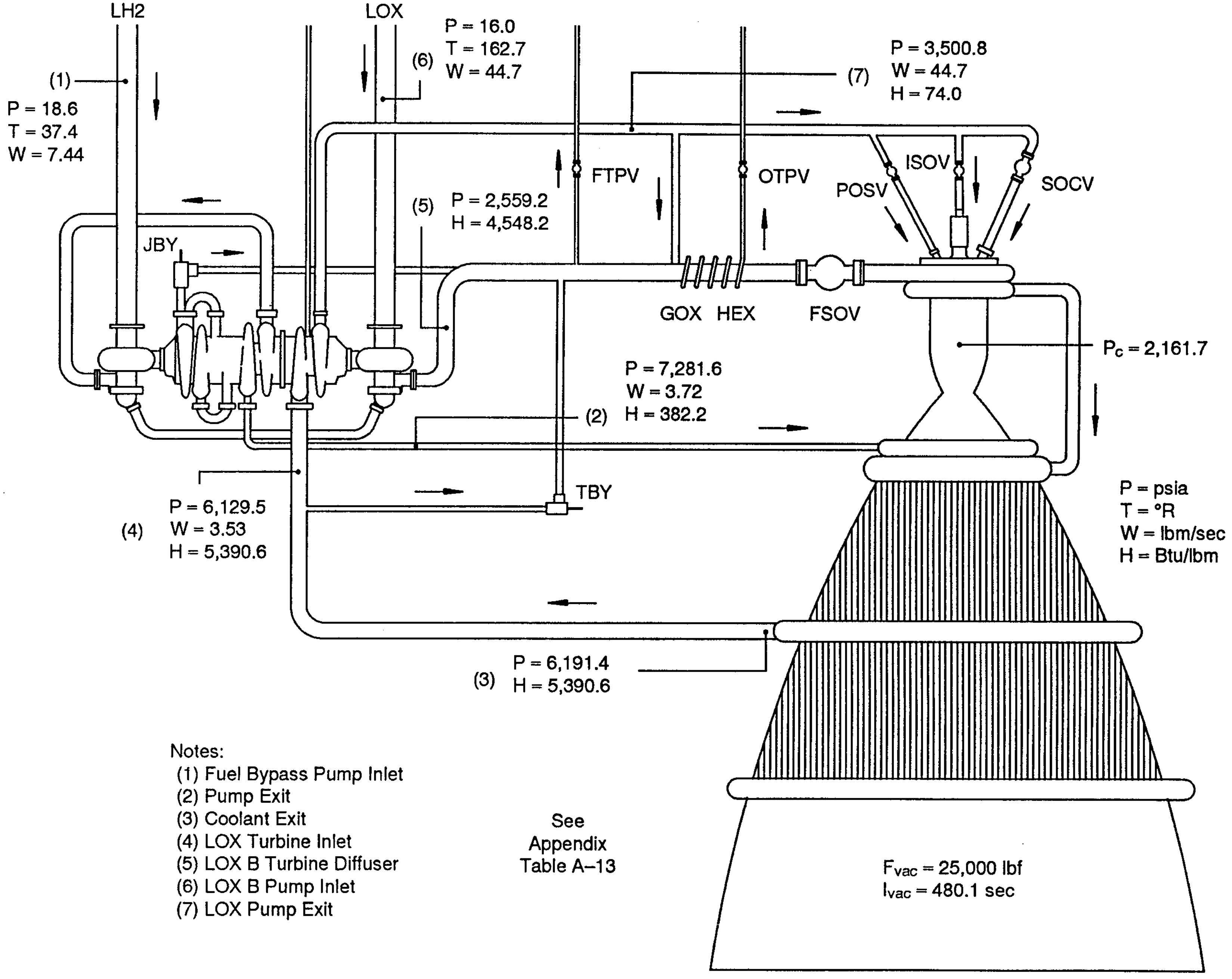


Figure 28. Split Expander — 50-Percent Bypass/30-Percent Enhancement — Four-Stage Pump

SECTION IV
TUBULAR CHAMBER PRELIMINARY DESIGN

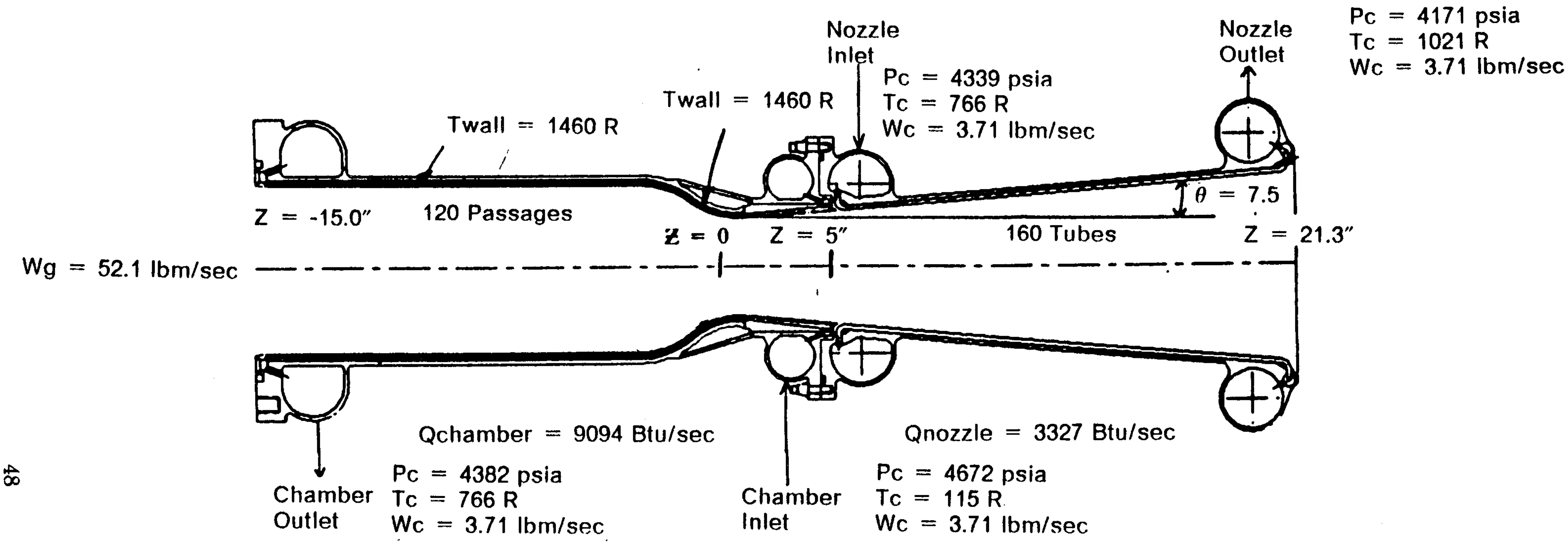
A. THERMAL ANALYSIS

The object of the chamber design effort was to prepare a preliminary design of a copper tubular thrust chamber that could be substituted for a milled channel thrust chamber in the Advanced Expander Test Bed (AETB). The AETB milled channel thermal design is shown in Figure 29. A key requirement of the design was that the tubular chamber match the AETB cycle requirements (i.e., the total heat regeneration had to be nearly equal to or higher than the milled channel chamber, and the pressure drop had to be equal or lower). Reoptimization of the AETB cycle based on the tubular chamber was not considered, since this would impact the AETB turbomachinery and control system design.

For the AETB-compatible thrust chamber preliminary design, NASA-Lewis Research Center (NASA-LeRC) recommended that the constant 18-percent enhancement used in the parametric study be modified to a variable enhancement of 40 percent in the thrust chamber decreasing to 20 percent at the throat, with a 30-percent transition in the converging section upstream of the throat. A thermal design study was initiated to evaluate the performance of a variable enhancement chamber based on a 50-percent bypass flow ratio and a minimum tube width of 0.070 in. The maximum allowable wall temperature was limited to 1460°R and maximum allowable hoop stress was limited to 90 percent of the yield stress. A minimum length of 12.0 in. (limited by required combustion length) was used because this best met AETB cycle requirements.

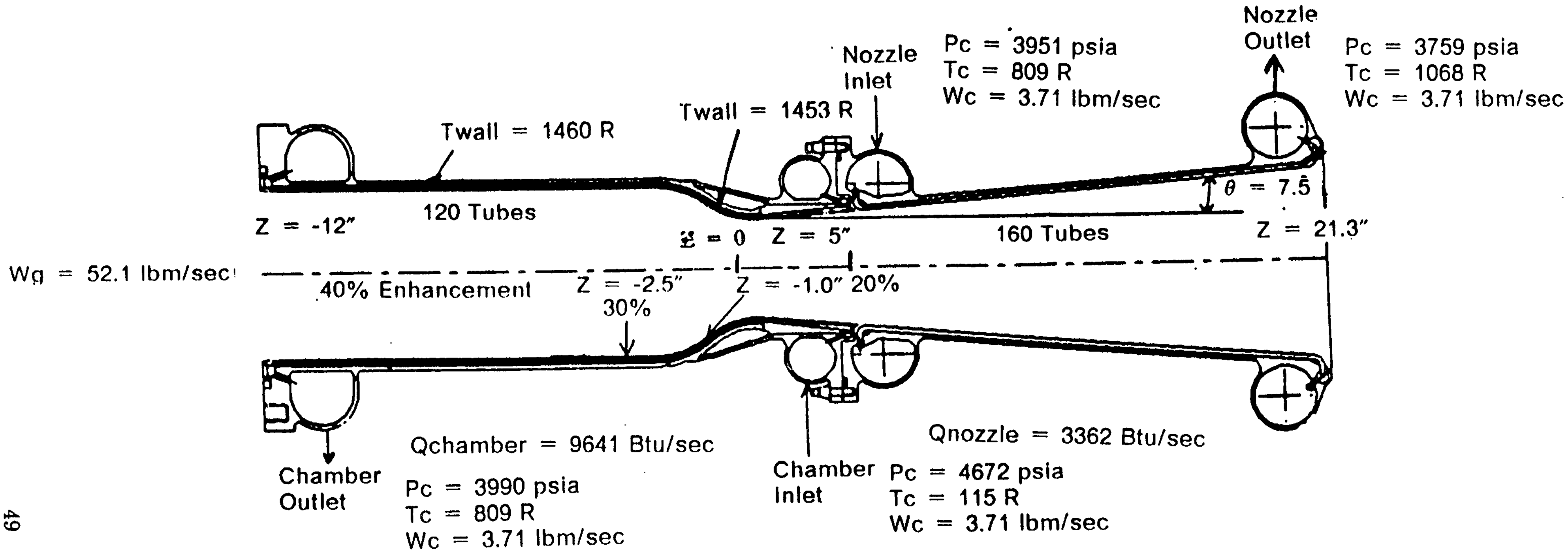
The initial variable enhancement configuration evaluated was based on the results of the parametric study and consisted of a counterflow cooled chamber with 120 tubes and a 50-percent bypass flow ratio. The thermal performance of this chamber (as summarized in Figure 30) shows that the coolant heat regeneration meets the cycle requirements; however, the coolant pressure drop is over 80 percent above the cycle value (913 psia versus 503 psia). Accordingly, the number of tubes was increased to 140, the maximum value consistent with a minimum tube width of 0.070 in. (The increase in the optimum number of tubes from 120 in the parametric analysis to 140 in the preliminary design was driven primarily by the lower AETB chamber pressure). The coolant pressure drop was thereby reduced to 378 psia. This was below the 503 psia allowable cycle limit, and the coolant heat regeneration was also acceptable (Figure 31). This design therefore meets the cycle requirements and maximum stress and temperature criteria as stated in paragraph II.C.2.

To ensure that problems would not arise during testing (in the event that the postulated variable enhancement was not representative of the actual chamber tube side heat transfer), the AETB thermal performance was evaluated based on other assumed heat flux profiles. The lower bound of chamber thermal performance was assumed to be a constant 18-percent enhancement. As shown in Figure 32, for this case the required cycle heat rejection would still be nearly met, and there is enough extra pressure margin to compensate for the small deficiency in heat rejection. A constant 30-percent enhancement, with a total heat regeneration comparable to the variable enhancement chamber was also evaluated. The maximum wall temperature is 1474°R which slightly exceeds the assumed 1460°R limit (Figure 33). This slight over-temperaturing could be eliminated by over-designing the variable enhancement chamber. By increasing the coolant pressure drop by 10 psia, the tube wall temperature could be decreased to the 1460°R allowable limit.



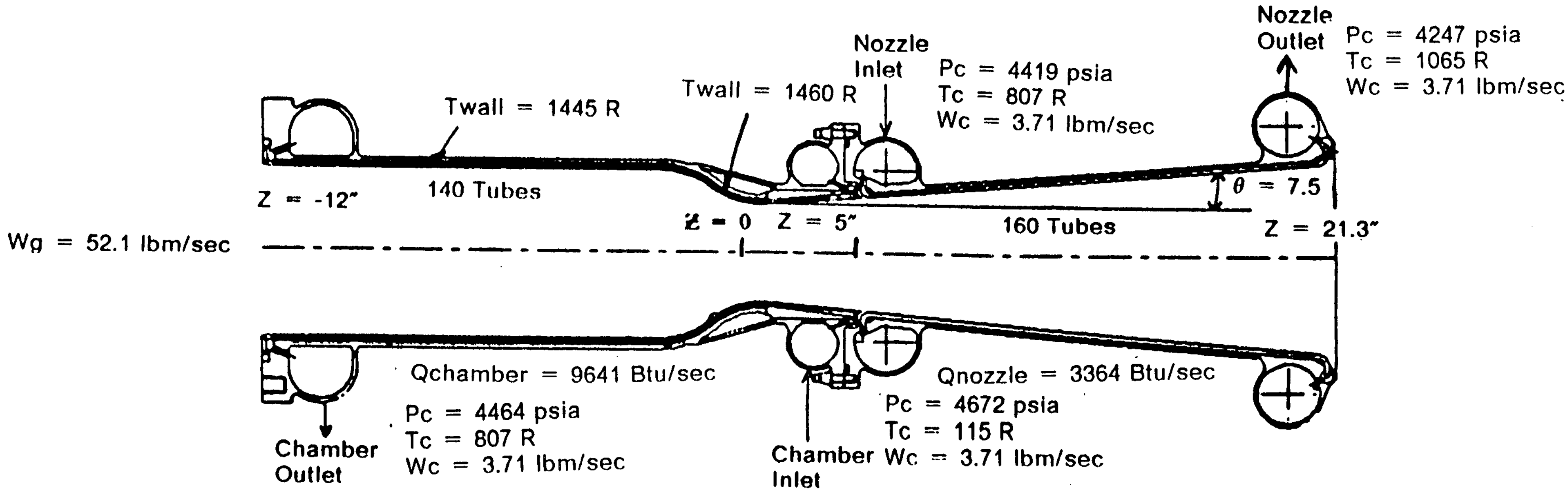
Coolant Parameter	Predicted Value	Cycle Value
Heat Rejection (Q) Btu/sec	12420	12370
Pressure Drop (ΔP) psia	501	503

Figure 29. Advanced Expander Test Bed Thermal Design Milled Chamber



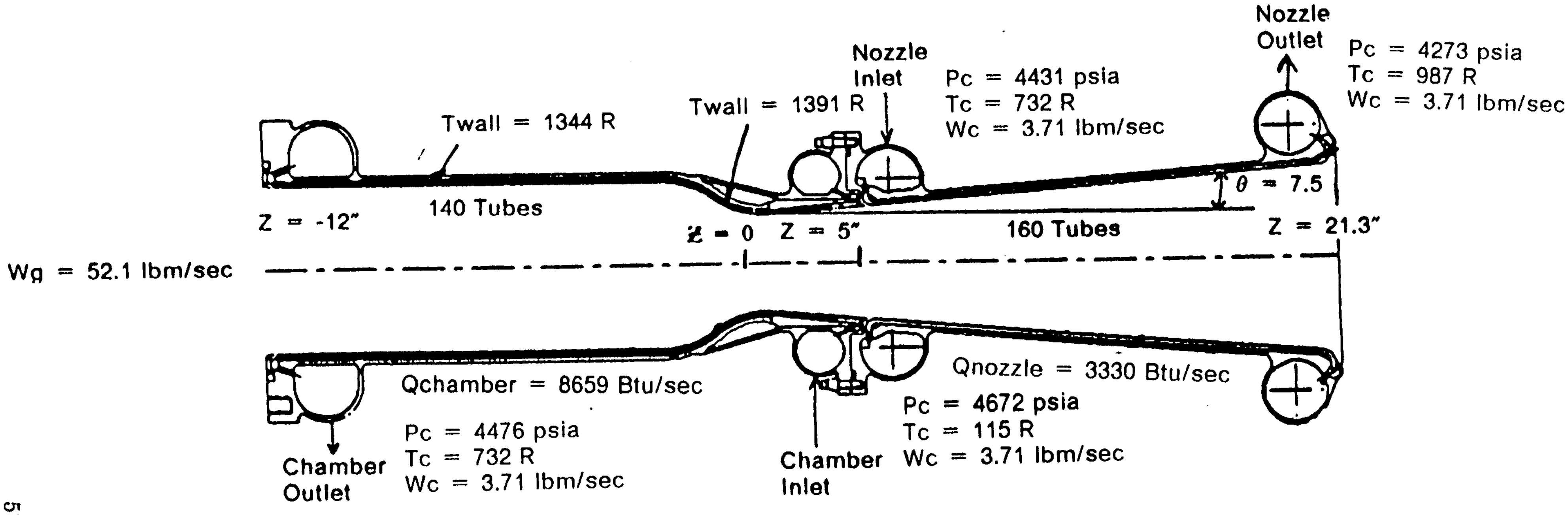
Coolant Parameter	Predicted Value	Cycle Value
Heat Rejection (Q) Btu/sec	13000	12370
Pressure Drop (ΔP) psia	913	503

Figure 30. Advanced Expander Test Bed Alternative Tubular Chamber Thermal Design — Variable Enhancement (Counterflow 120 Tubes)



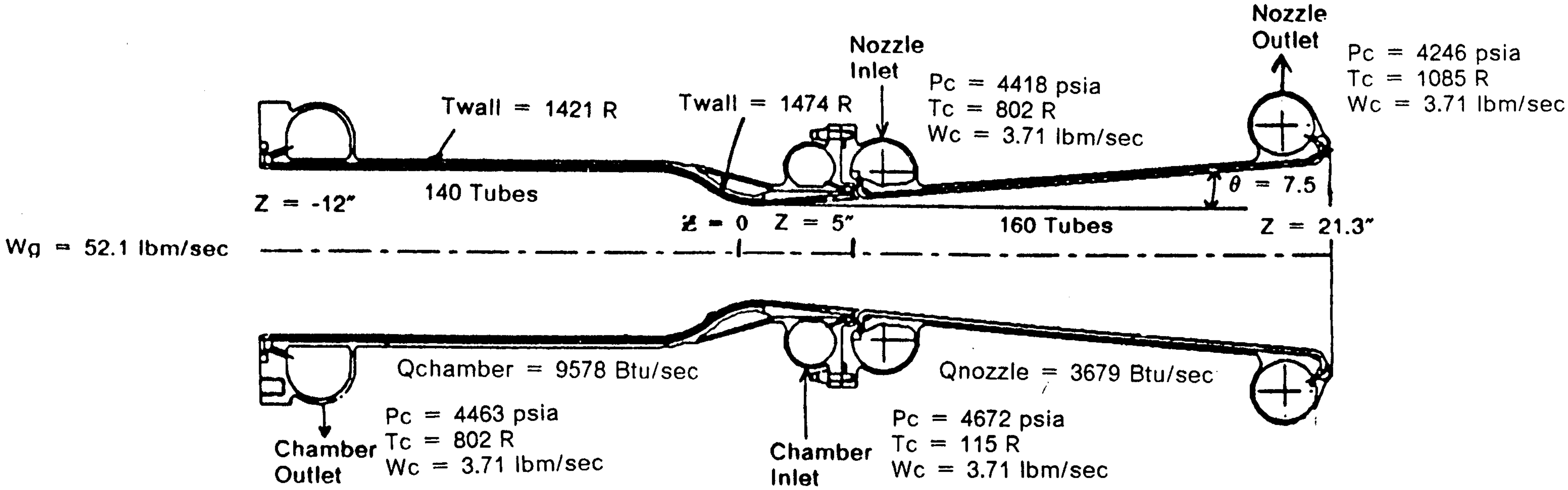
Coolant Parameter	Predicted Value	Cycle Value
Heat Rejection (Q) Btu/sec	13010	12370
Pressure Drop (ΔP) psia	425	503

Figure 31. Advanced Expander Test Bed Alternative Tubular Chamber Thermal Design — Variable Enhancement (Counterflow 140 Tubes)



Coolant Parameter	Predicted Value	Cycle Value
Heat Rejection (Q) Btu/sec	11990	12370
Pressure Drop (ΔP) psia	399	503

Figure 32. Advanced Expander Test Bed Alternative Tubular Chamber Thermal Design — Constant 18-Percent Enhancement (Counterflow 140 Tubes)



Coolant Parameter	Predicted Value	Cycle Value
Heat Rejection (Q) Btu/sec	13260	12370
Pressure Drop (ΔP) psia	426	503

Figure 33. Advanced Expander Test Bed Alternative Tubular Chamber Thermal Design — Constant 30-Percent Enhancement (Counterflow 140 Tubes)

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The AETB conical nozzle extension is designed specifically for series flow operation with the milled-passage chamber. The tubular chamber has better thermal performance than the milled-passage chamber; consequently, both the coolant temperature and pressure entering the Haynes-230 tubular nozzle are higher for the tubular chamber. This difference results in a slight overstressing of the Haynes tube at the nozzle exit (94 percent versus 90 percent of yield allowable). In addition, the ultimate tube temperature margin (UTTM) is 278°R which is slightly below the 300°R UTTM Pratt & Whitney (P&W) design practice for Haynes-230. By limiting the chamber pressure to 1450 psia rather than the 1500 psia AETB design point the Haynes nozzle meets the stress and UTTM design criteria. The designated 1450 psia chamber is still well above the 1200 psia AETB operating point.

Summarizing, the 140 tube variable enhancement chamber design meets the AETB cycle requirements. Moreover, the Test Bed chamber will perform satisfactorily whether the tubes exhibit variable or constant heat transfer enhancement behavior.

B. MECHANICAL DESIGN

Design data for the AETB compatible tubular chamber configuration are presented in Table 11. The preliminary design concept is shown in Figure 34. The 140 tubes are joined by an electroformed copper jacket that forms a coolant seal at the tube ends where the inlet and exit manifolds attach. The jacket seals the cooling passages and accommodates the chamber pressure thrust loads. The tubes are straight at the nozzle end (coolant inlet) and are capsealed during electroforming. The tubes are hooked at the injector end (coolant exit). Flow from the hooked ends continues through holes in the electroformed jacket and into the exit manifold. The hooked ends provide a smooth and undisturbed flow path for the coolant entering the exit manifold to minimize exit manifold losses (Figure 35).

TABLE 11. — TEST BED PRELIMINARY DESIGN DATA

Chamber Coolant Liner Material:	NASA Z
Chamber Construction:	Tubular
Number of Tubes:	140
Chamber Contraction Ratio:	3.0
Divergent Nozzle Area Ratio:	7.5
Chamber Length:	12 in.
Divergent Nozzle Length:	21.3 in.
Throat Diameter:	3.22 in.
Chamber Diameter:	5.56 in.
Chamber Volume:	244 in.
Chamber Wall Surface Area (Injector to Throat):	193 in.
Chamber Characteristic Length, (L*):	29.96 in.
Maximum Hot-Wall Temperature	1459°R
Allowable Hot-Wall Temperature	1460°R

The coolant in the chamber is counterflow. The inlet manifold and exit manifold are similar in design and are both toric with constant-diameter cross sections. Both manifolds are made up of inner and outer rings welded together. The combustion chamber inlet manifold and nozzle inlet manifold bolt together with 0.5-inch diameter through bolts.

The combustion chamber exit manifold also bolts to the injector with 0.5-inch diameter through bolts. At both combustion chamber interfaces, the seal groove is in the combustion chamber side. To minimize the blow-off loads, seal diameters are kept to a minimum. The torroidal plenums of the inlet and exit manifolds are located outside of the bolt circle to allow the bolt circles to be as close to the seals as possible. To allow access to the chamber coolant tubes a 0.375-inch diameter transfer hole is located between the bolt holes. The size and number of these

holes creates adequate flow area to minimize pressure drop. Integral standoffs are machined into the outer rings of the inlet and exit manifolds as a point of attachment for welding coolant plumbing. The piping connected to both the inlet and exit manifolds is similar. Both manifolds are welded to long-radius 90° elbows. The inlet manifold elbow is 1.25-inch schedule 80 pipe with a flow diameter of 1.28 in. The exit manifold is 22.0-inch elbow with a flow diameter of 1.50 inches.

The tube material is a high thermal conductivity copper alloy, either NASA-Z, a silver zirconium alloyed precipitation hardened copper, or GlidCop AL-15, an alumina dispersion strengthened copper. The NASA-Z has proven life-cycle fatigue properties and the GlidCop maintains its strength at temperature above the precipitation temperature of NASA-Z. The tube maximum hot-wall design point is 1460°R. The tubes have a constant 0.016-inch wall thickness, and are booked in the throat region and transition to round at both ends. Booking is necessary to maintain the correct flow area and velocity.

The tubes are capped at the nozzle end with electrodeposited copper (ED-Cu). Entrance to the tubes is formed by a circumferential channel cut through the copper jacket and outer tube walls. The cut depth is controlled through the crown of the tubes, but not beyond the electroformed copper between the crowns, to prevent hydrogen from leaking between tubes to the coolant side (Figure 36).

At the front end of the chamber, the tubes look radially outward through the jacket. The inlet and exit manifolds are manufactured as separate assemblies before chamber attachment. The inner and outer rings are machined, welded together, and then remachined.

The copper tubes are rotodrawn from thick walled cylindrical blanks. They are drawn to a straight tube with varying circular cross sections and an elongated hourglass shape. The right-angle bend for the exit is formed, and then the tube is formed to the chamber contour. The contoured tube is ovalized (booked) at most axial locations except near the ends. The flat sides of the tubes are angled 2.57 degrees for proper tube tangency. The tubes are then fit around a mandrel for fixturing during electroforming and subsequent chamber machining. Excess stock is left on both ends so that the tubes can be held to the mandrel. The tube and mandrel assembly rotates in a plating tank, where the copper jacket is formed. After the jacket is electrodeposited to 0.500-inch thickness, the ends are machined to accept the inlet and exit manifolds. The entrance channel is then cut through the jacket and tube crowns. The manifolds are fit 0.000 to 0.004 in. tight on the copper jacket. Manifolds are either welded or electroformed to the jacket.

At the coolant entrance, the tubes extend to the chamber and nozzle interface. The tubes are sealed with an electroformed cap. The tube ends are filled with wax, the exposed wax is activated, and the ends are capped with ED-Cu. This capping may be done before or after the entrance manifold attachment depending on whether the manifolds are attached by welding or electroforming.

FOLDOUT FRAME

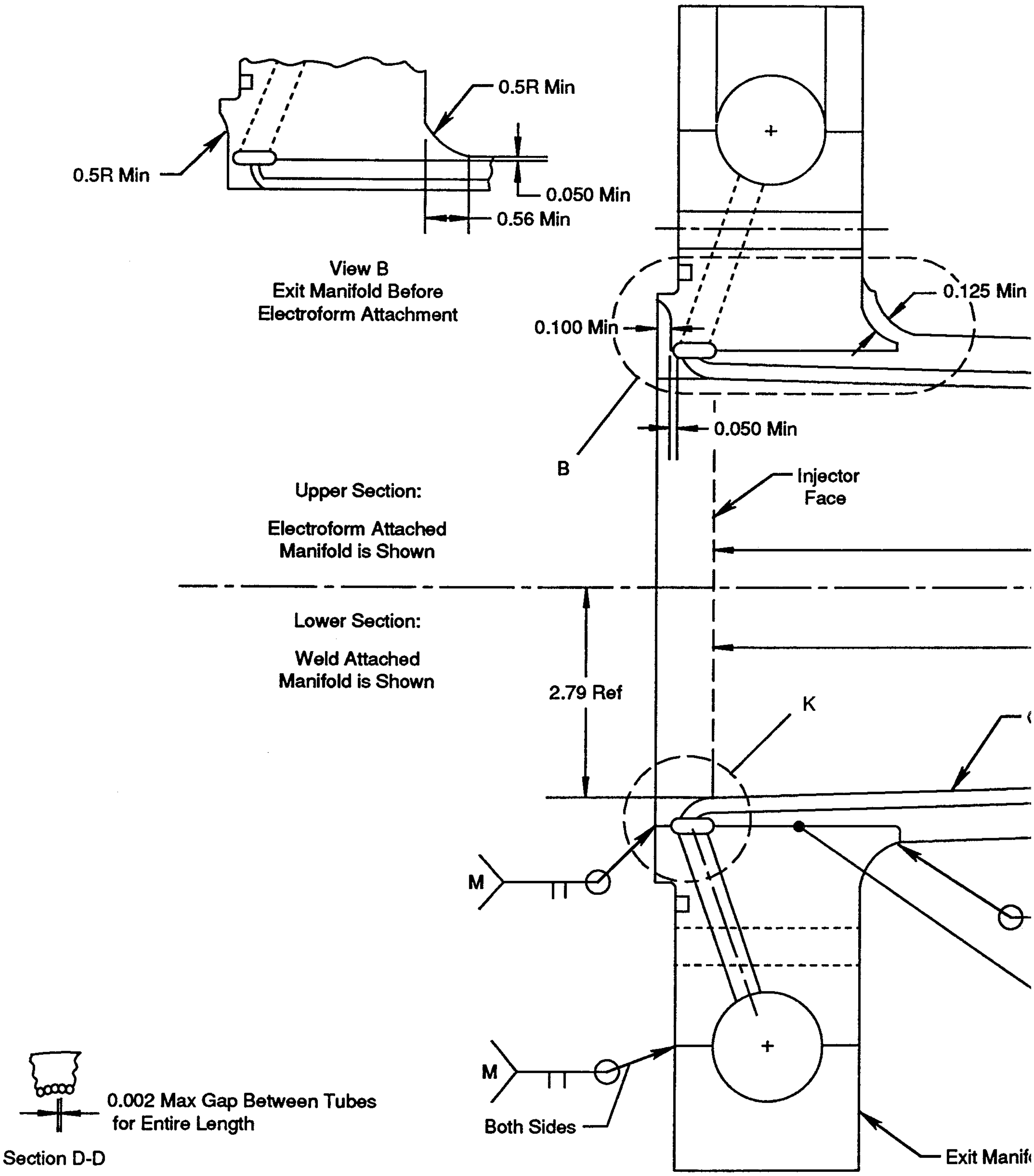
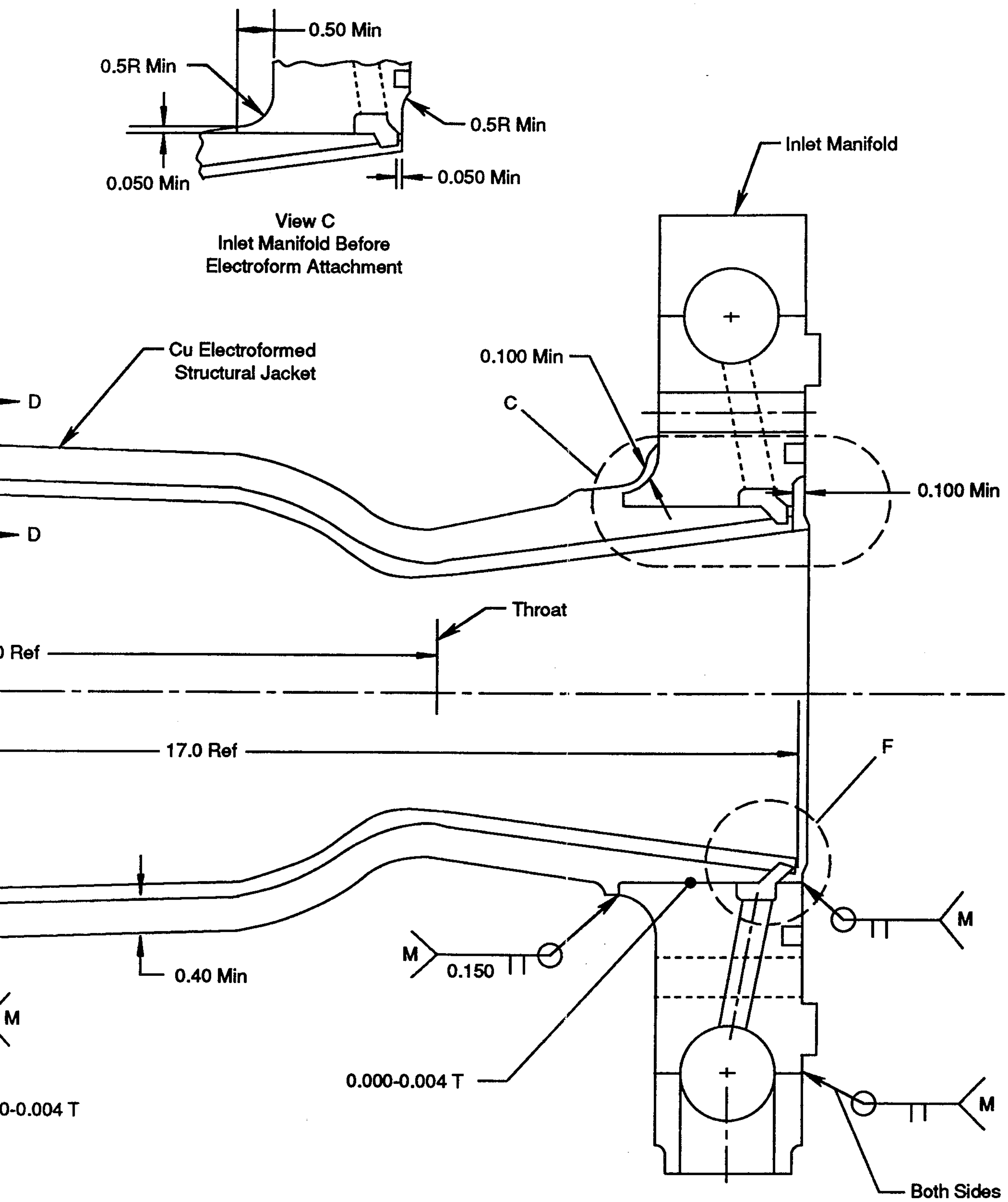


Figure 34. Copper Tubular Combustion Chamber — Advanced Expander Test Bed Alternate Design

FOLDOUT FRAME



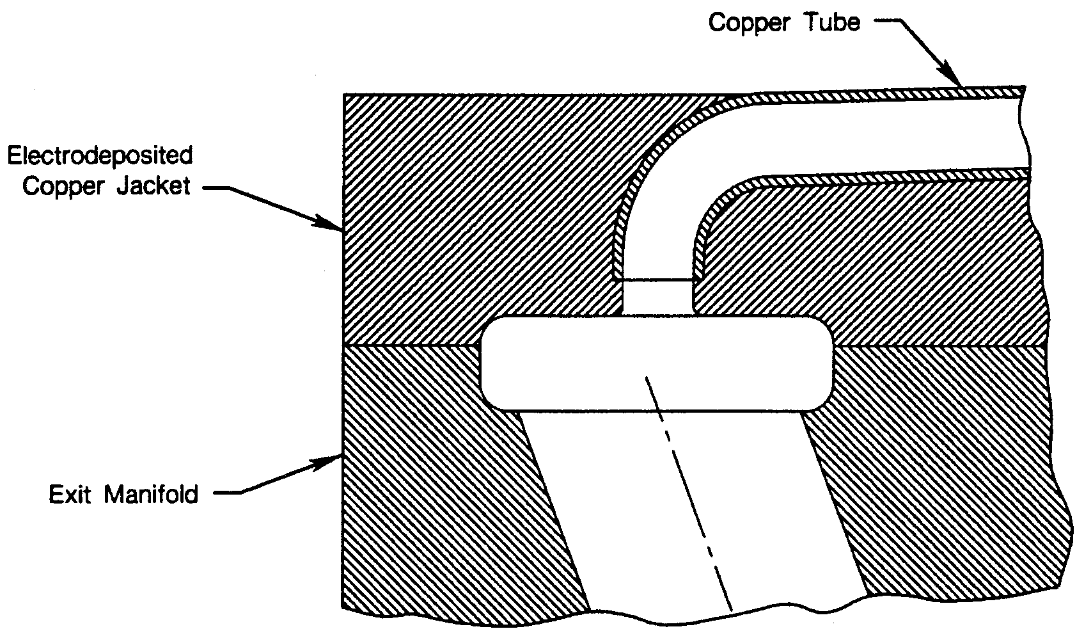


Figure 35. Coolant Exit (See View K on Figure 34)

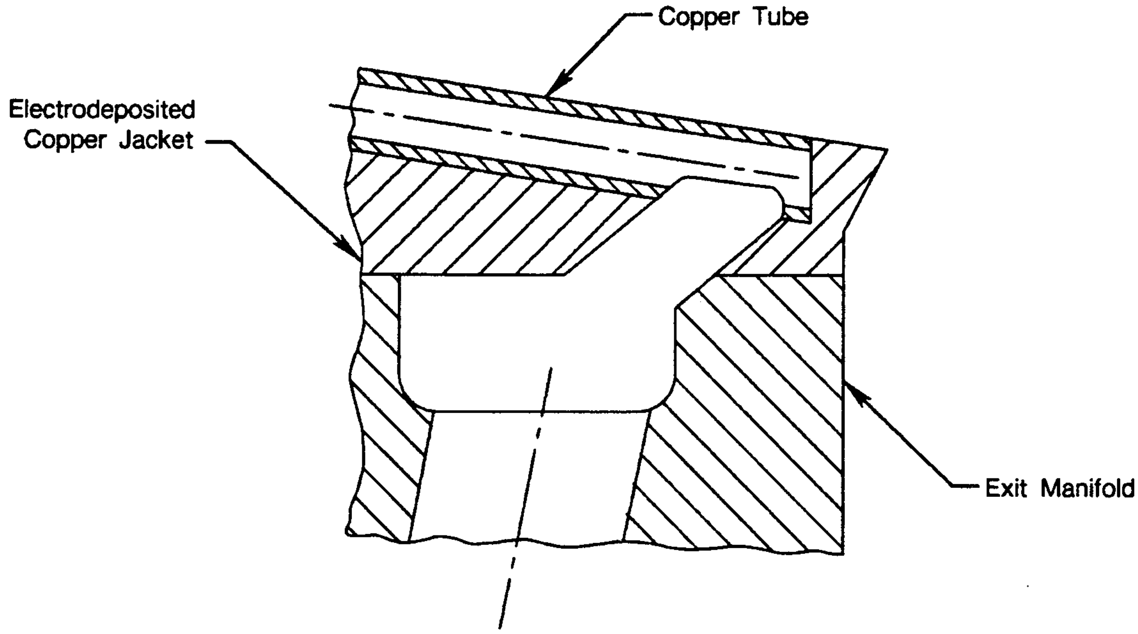


Figure 36. Coolant Entrance Through Tube Outer Walls (See View F on Figure 34)

C. STRUCTURAL AND LIFE ANALYSIS

The copper tubular thrust chamber was designed to meet the AETB minimum life design criteria of 100 cycles and 2.0 hours life. The thicknesses of the ED-Cu jacket and manifolds are based on design point pressure loads, and sized to provide minimum safety factors of 1.2 yield and 1.5 for ultimate. A significant thermal gradient exists between the manifolds and attachment flanges at both the front and aft flanges of the combustion chamber. Selection of a manifold

material with a low coefficient of expansion (Incoloy 909) reduces the thermal growth differential between flanges to acceptable limits.

1. Jacket Buckling Analysis

Figure 37 shows the axial load in the ED-Cu jacket based on internal pressure loads on the chamber and nozzle. A buckling analysis of the jacket determined the jacket has a buckling factor of 30. Therefore, there is no risk of buckling due to the compressive axial load at the throat.

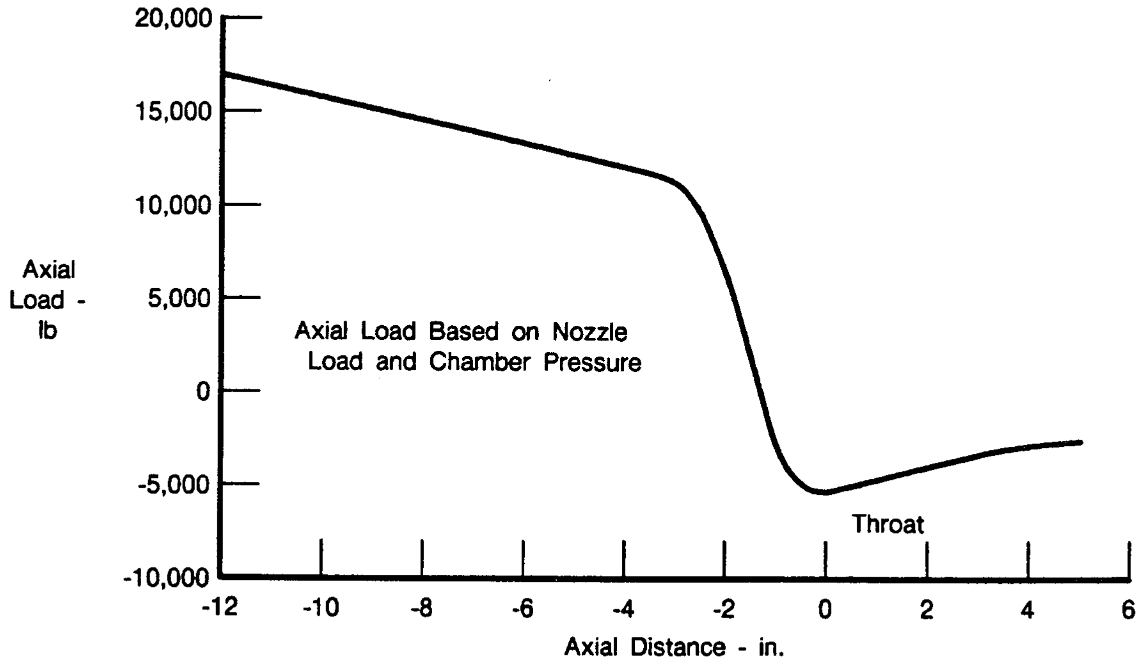


Figure 37. Advanced Expander Test Bed Tubular Chamber Structural Jacket Axial Load Distribution

2. Liner Life Analysis

Review of prior combustion chamber liner failures indicate failures typically occur slightly upstream from the throat. This is usually the region of maximum heat flux and largest temperature gradient between the liner and structural jacket. Figure 38 shows the average temperature of the tube wall and the coolant temperature. The electroformed copper jacket temperature is assumed to be equivalent to the coolant temperature. As indicated in Figure 35, the maximum thermal gradient between the liner wall and the jacket occurs 1.0 in. upstream of the nozzle throat (Z=1.0 in.); therefore, this location was selected as the potential life-limiting location for the tubular liner.

The tube wall was assessed for low-cycle fatigue (LCF) life and stress rupture life. The LCF life assessment is based upon the calculated concentrated strain at steady-state conditions. Minimum strain is assumed to be zero, since no transient analysis was performed. Steady state strains are dependent upon the mechanical and thermal loading within the tubes and jacket. Mechanical loads are caused by coolant static pressure and combustion static pressure at the appropriate axial location. Thermal loads are dependent upon the temperature distribution within the tube and attached structural jacket. Steady-state isotherms for the two-dimensional temperature model at Z = −1.0 in. are shown in Figure 39. The structural model (Figure 40)

shows temperature effects, in addition to the pressures and boundary conditions. Using symmetry, the structural analysis was accomplished using half a tube and the corresponding arc length of the structural jacket.

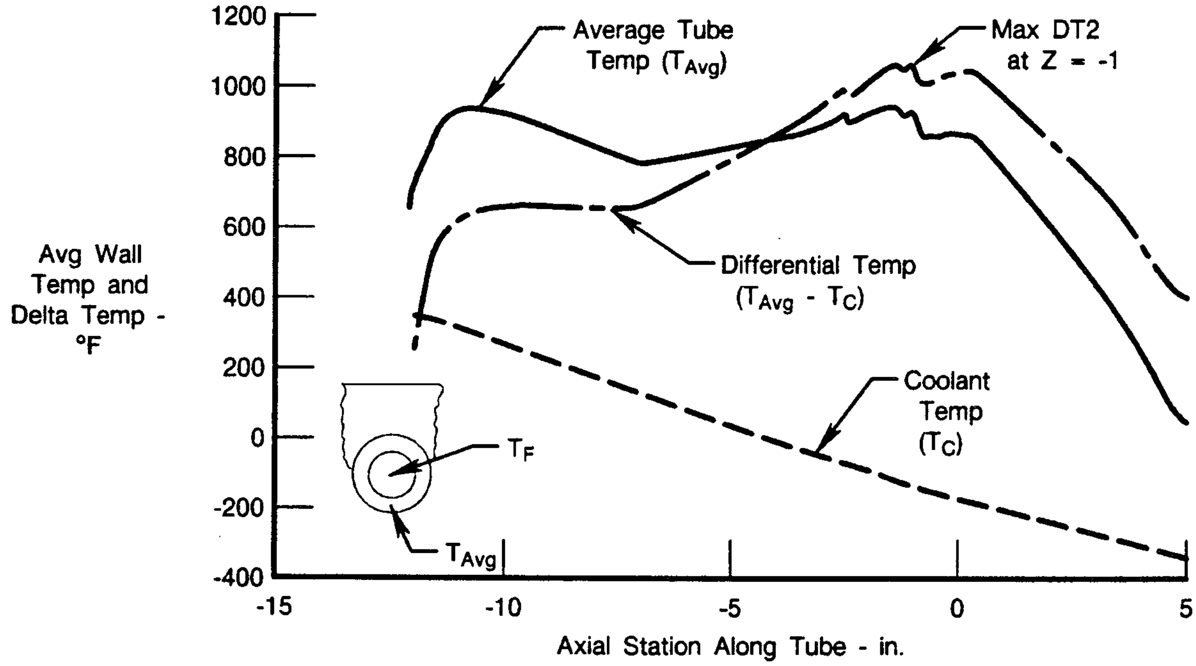


Figure 38. Advanced Expander Test Bed Alternative Tube Chamber Coolant and Tube Temperature Profiles

	Temperature°R
1)	340.7
2)	527.1
3)	713.4
4)	899.7
5)	1086
6)	1272
7)	1458

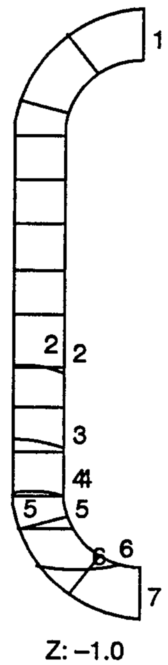


Figure 39. Tube Isotherms 1.0 in. Upstream of Chamber Throat (Z=−1)

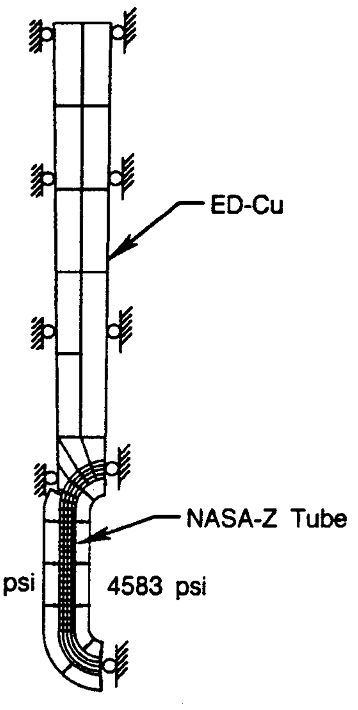


Figure 40. NASTRAN Two-Dimensional Structural Modes

The electrodeposited jacket provides structural support to the tubular liner and bonds the tube bundle together, thus eliminating the need for a brazed tube assembly. As seen in Figure 40, the copper jacket/tube bond joint was assumed to occur along the upper surface of the tubes, and not along the flat tube sides. Therefore, the tube sides are allowed to deflect tangentially based upon the gap between tubes. Figure 41 shows that the tube side deflects tangentially 0.00125 in. for combined thermals and pressure. This deflection is primarily caused by the rounding of the tube from the internal coolant pressure. A significant amount of bending stress occurs at the liner side of the tube, as shown by the major principal stress contour plot in Figure 42. An elastic maximum principal stress of +91 ksi occurs on the coolant side of the tube liner wall. This stress is well over the minimum yield strength of 15 ksi for that location. However, assuming the tubes have deflected enough to consume the tangential gap between tubes, no further yielding is expected to take place, since the tube will be constrained from any further rounding. This approaches a deflection-controlled problem, based on gap size, and therefore the resulting strain is approximately equivalent to the total strain. The corresponding Von Mises total strain is 0.60 percent on the coolant side and 0.68 percent on the chamber side of the liner wall.

The LCF life of the NASA-Z tube wall is based on the predicted strain range, temperature, and material LCF characteristics. Typical LCF characterization for NASA-Z (Reference 3) is plotted in Figure 43. Using these data, the strain range of 0.68 percent on the hot wall will result in an acceptable LCF life of 3660 cycles. The average pressure induced stress across the tube wall results in an acceptable 10 hour stress rupture life.

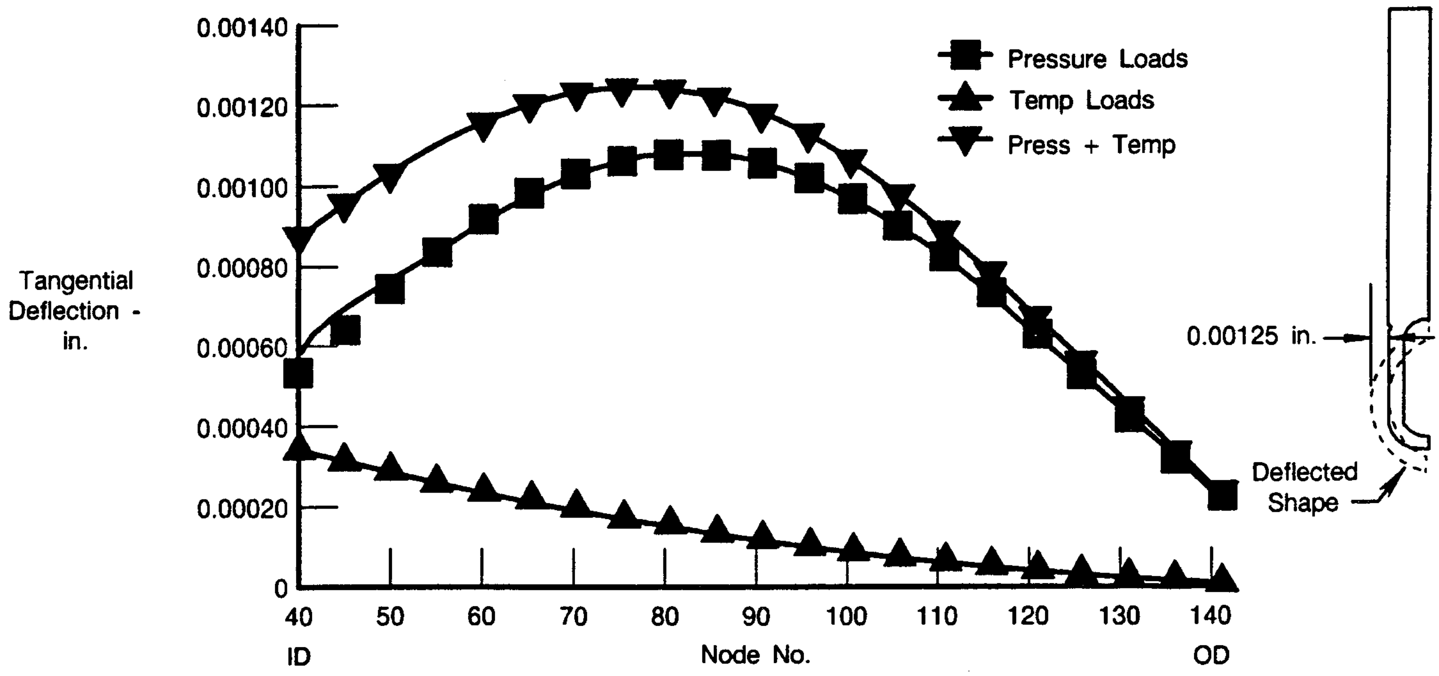


Figure 41. Tube Tangential Deflection

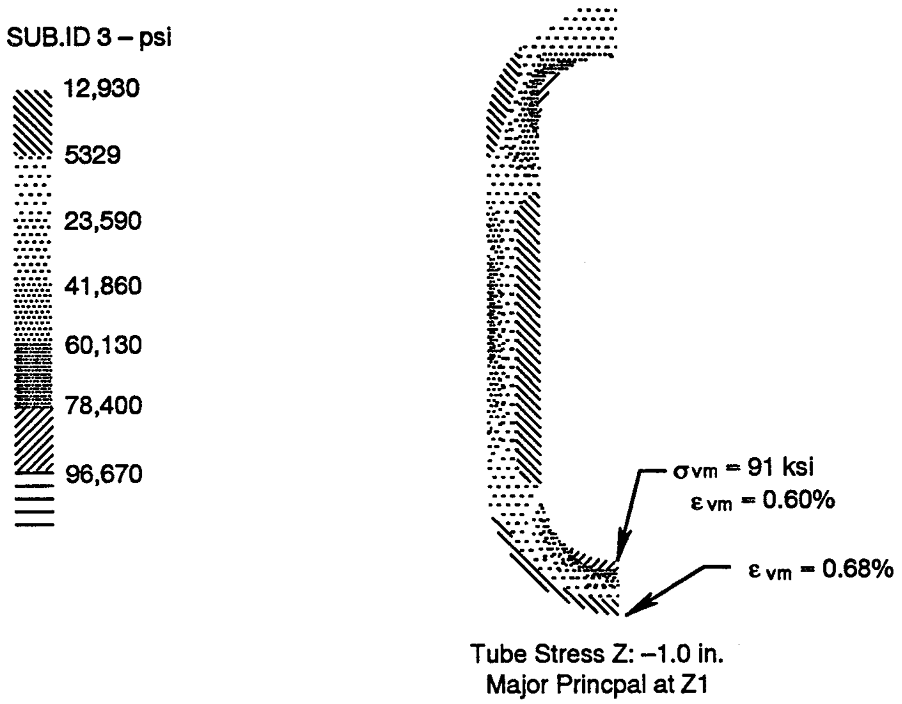


Figure 42. Principal Stress Contour Plot

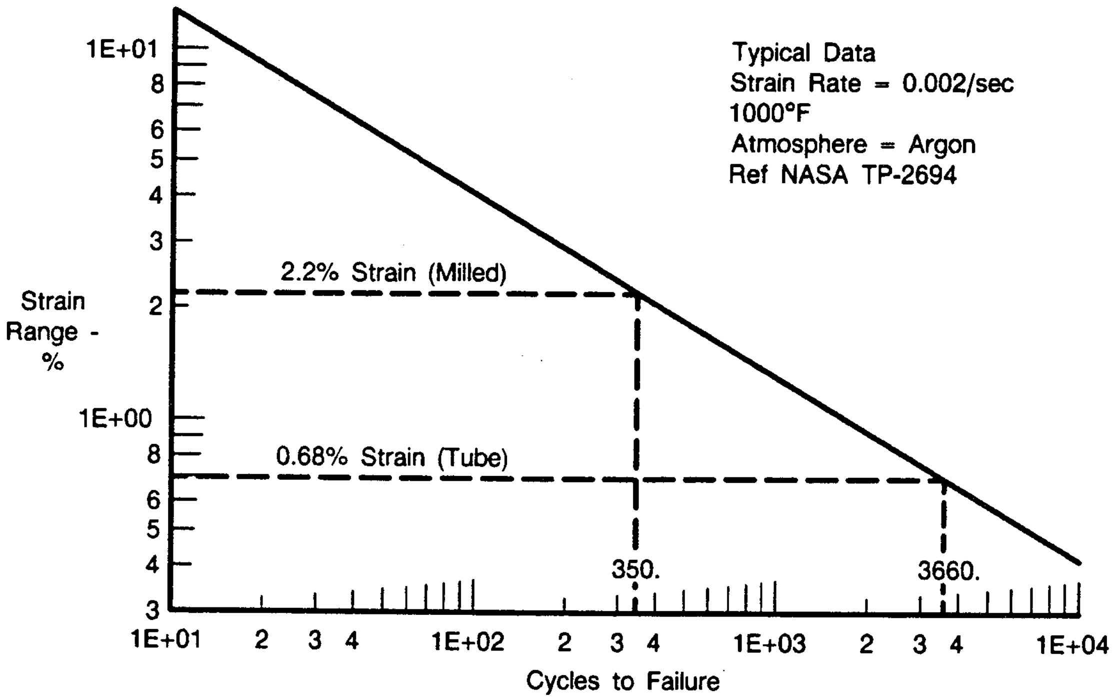


Figure 43. NASA-Z Low-Cycle Fatigue — Tube Chamber Versus Milled Chamber

3. Milled Chamber Life Comparison

A comparison to the milled chamber design was made to estimate the potential life improvement for a tubular liner design. The milled chamber geometry, temperatures, and pressures are based on an equivalent milled chamber design (i.e., the AETB baseline thrust chamber). An AETB chamber axial location 0.64 in. upstream of the nozzle throat was selected using the same criterion as the tube chamber: maximum thermal gradient between the coolant and the average hot wall temperature. The milled chamber was analyzed using the simplified life prediction method defined in NASA CR-168261 (Reference 4). The Von Mises strain and corresponding LCF life comparison are presented in Table 12. This comparison indicates a tubular chamber design is plastically strained much less than a milled chamber design, and thus will tolerate more firings before crack initiation.

TABLE 12. — VON MISES STRAIN AND CORRESPONDING LCF LIFE COMPARISON

Configuration	*Hot Wall Temperature*	*Strain*	*LCF Life*	*Normalized Life*
Tubular	1000°F	0.68%	3660 Cycles	10 X
Milled	1000°F	2.2 %	350 Cycles	1 X

The analysis approach employed is limited, and may not predict the actual life of the hardware for several reasons. First, the high plastic strains caused by thermals and pressures may be more accurately calculated using a plastic rather than elastic finite element approach. Also, due to the high compressive stress and temperature, creep relaxation should also be considered in the analysis approach if the combination of dwell time, temperature, and stress is sufficient to initiate material creep. Secondly, since fatigue life is dependent upon the total strain range the material experiences throughout an entire firing cycle, a complete cycle should be

evaluated, rather than only a steady-state condition. Ideally, this should include transient temperature, pressure, and boundary conditions for chilldown, start, steady state, and shutdown. This analysis approach is considerably more tedious and costly than the elastic analysis method used here, and still has some uncertainty. The method employed is believed to provide a valid relative comparison.

The membrane and bending stress/strain distribution within the tube is highly sensitive to assembly clearance between tubes. For comparison, the structural model was run with tangential boundary constraints along the flat side of the tube to simulate a zero clearance between tubes. Results show the bending stress across the ID of the tube reverses direction and becomes highly tensile on the chamber side and compressive on the coolant side. Thermals tend to govern the stress distribution within the tube ID when no gap exists between tubes and pressures tend to control stresses when there is a 0.0025-inch clearance (2×0.00125 in.) between tubes. Thus, accurate prediction of tube stress-strain history and subsequent LCF life is dependent upon the clearance between tubes. However, either condition still results in much lower strains than the 2.2 percent predicted for the milled-chamber design.

Currently, P&W is developing a life prediction methodology for tubular thrust chambers that will address the above concerns. This methodology will be used to predict the cyclic life of subscale tubular chamber designs to be tested at NASA-LeRC. Results of the testing will be used to correlate the life prediction methodology.

SECTION V
RECOMMENDATIONS

Results of this study have shown a significant performance and life advantage for tubular copper thrust chambers over milled channel chambers in expander cycle space engines. On the basis of these results, the development of tubular copper thrust chambers should be vigorously pursued as key technology for such engines. Specific areas that should be addressed include the following:

- Development of tube bonding techniques (i.e., electroforming, plasma spraying or brazing) that do not significantly compromise copper properties

- A more detailed analysis and experimental confirmation of the low-cycle fatigue and creep rupture life improvement of tubular construction relative to milled channel construction

- Experimental determination of the heat transfer enhancement associated with tubular construction and development of better models to scale results from these tests.

Some of the above work is already on-going in NASA-Lewis Research Center programs of analysis and subscale testing. A logical extension of this work would be the design, fabrication, and test of a full-scale thrust chamber. The design prepared under this program is aimed at providing a thrust chamber that would be suitable for this purpose and compatible with the Advanced Expanded Test Bed (AETB).

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APPENDIX A
DETAILED CYCLE DATA

TABLE A-1. — OPTIMIZED SPLIT EXPANDER

ENGINE PERFORMANCE PARAMETERS

CHAMBER PRESSURE	1754.9
VAC ENGINE THRUST	25000.
TURBINE PRESSURE RATIO	2.20
TOTAL ENGINE FLOW RATE	52.08
DEL. VAC. ISP	480.1
THROAT AREA	6.97
NOZZLE AREA RATIO	1000.0
NOZZLE EXIT DIAMETER	94.20
ENGINE MIXTURE RATIO	6.00
ETA C*	0.993
CHAMBER COOLANT DP	424.
CHAMBER COOLANT DT	790.
NOZZLE/CHAMBER Q	14357.

ENGINE STATION CONDITIONS

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	18.6	37.4	7.45	-107.5	4.37
B.P. EXIT	100.8	38.5	7.45	-103.0	4.39
PUMP INLET	100.8	38.5	7.45	-103.0	4.39
1ST STAGE EXIT	2370.5	71.5	7.45	41.9	4.41
JBV INLET	2323.1	71.9	2.60	41.9	4.38
JBV EXIT	1974.6	74.6	2.60	41.9	4.15
2ND STAGE EXIT	3782.8	90.3	4.85	128.9	4.46
PUMP EXIT	5189.1	108.3	4.85	214.4	4.52
COOLANT INLET	5137.2	108.8	4.85	214.4	4.50
COOLANT EXIT	4712.8	898.9	4.85	3174.5	0.87
TBV INLET	4665.7	899.2	0.24	3174.5	0.86
TBV EXIT	2067.6	916.9	0.24	3174.5	0.40
O2 TRB INLET	4665.7	899.2	4.61	3174.5	0.86
O2 TRB EXIT	4130.5	877.2	4.61	3083.4	0.79
H2 TRB INLET	4130.5	877.2	4.61	3083.4	0.79
H2 TRB EXIT	2193.4	772.5	4.61	2667.6	0.50
H2 TRB DIFFUSER	2165.0	772.6	4.61	2667.6	0.49
H2 BST TRB IN	2143.3	772.6	4.61	2667.6	0.49
H2 BST TRB OUT	2119.5	770.8	4.61	2660.3	0.49
H2 BST TRB DIFF	2112.5	770.9	4.61	2660.3	0.48
O2 BST TRB IN	2091.4	771.0	4.61	2660.3	0.48
O2 BST TRB OUT	2079.0	770.0	4.61	2656.3	0.48
O2 BST TRB DIFF	2078.0	770.0	4.61	2656.3	0.40
H2 TANK PRESS	18.6	789.9	0.0076	2682.2	0.0044
GOX HEAT EXCH IN	2067.6	777.4	4.84	2682.2	0.47
GOX HEAT EXCH OUT	2057.2	776.8	4.84	2680.1	0.47
MIXER HOT IN	2057.2	776.8	4.84	2680.1	0.47
MIXER COLD IN	1974.6	74.6	2.60	41.9	4.15
MIXER OUT	1954.4	519.8	7.44	1759.2	0.65
FSOV INLET	1954.4	519.8	7.44	1759.2	0.65
FSOV EXIT	1905.5	520.0	7.44	1759.2	0.64
CHAMBER INJ	1886.5	520.0	7.44	1759.2	0.63
CHAMBER	1754.9				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	16.0	162.7	44.7	-61.9	70.99
B.P. EXIT	135.2	165.3	44.7	62.3	70.84
PUMP INLET	135.2	165.3	44.7	62.3	70.84
PUMP EXIT	2842.1	178.0	44.7	71.7	71.38
O2 TANK PRESS	16.0	400.0	0.076	204.7	0.12
OSOV INLET	2813.7	178.1	6.7	71.7	71.34
OSOV EXIT	1969.6	181.4	6.7	71.7	70.03
OCV INLET	2813.7	178.1	37.9	71.7	71.34
OCV EXIT	1969.6	181.4	37.9	71.7	70.03
CHAMBER INJ	1949.9	181.5	44.6	71.7	69.99
CHAMBER	1754.9				

* VALVE DATA *

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	348.	0.10	2.60	34.87
TBV	2598.	0.01	0.24	5.00
FSOV	49.	1.92	7.44	
OCV	844.	0.23	44.64	

* INJECTOR DATA *

INJECTOR	DELTA P	AREA	FLOW
FUEL	132.	1.22	7.44
LOX	195.	0.57	44.64

TABLE A-1. — OPTIMIZED SPLIT EXPANDER (CONTINUED)

*** TURBOMACHINERY PERFORMANCE DATA ***

*** H2 BOOST TURBINE ***

EFFICIENCY (T/T)	0.864
EFFICIENCY (T/S)	0.619
SPEED (RPM)	41[illegible]
MEAN DIA (IN)	1.86
EFF AREA (IN2)	1.97
U/C (ACTUAL)	0.553
MAX TIP SPEED	432.
STAGES	1
GAMMA	1.40
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.02
HORSEPOWER	48.
EXIT MACH NUMBER	0.07
SPECIFIC SPEED	131.51
SPECIFIC DIAMETER	0.65

*** H2 BOOST PUMP ***

EFFICIENCY	0.765
HORSEPOWER	48.
SPEED (RPM)	41344.
S SPEED	3045.
HEAD (FT)	2701.
DIA. (IN)	2.43
TIP SPEED	439.
VOL. FLOW	761.
HEAD COEF	0.450
FLOW COEF	0.201

*** H2 TURBINE ***

EFFICIENCY (T/T)	0.832
EFFICIENCY (T/S)	0.811
SPEED (RPM)	125000.
HORSEPOWER	2711.
MEAN DIA. (IN)	2.77
EFF AREA (IN2)	0.24
U/C (ACTUAL)	0.469
MAX TIP SPEED	1602.
STAGES	2
GAMMA	1.40
PRESS RATIO (T/T)	1.88
PRESS RATIO (T/S)	1.92
EXIT MACH NUMBER	0.14
SPECIFIC SPEED	37.51
SPECIFIC DIAMETER	1.79

*** H2 PUMP ***

	STAGE ONE	STAGE TWO	STAGE THREE
EFFICIENCY	0.658	0.677	0.677
HORSEPOWER	1526.	598.	587.
SPEED (RPM)	125000.	125000.	125000.
SS SPEED	11322.		
S SPEED	765.	881.	887.
HEAD (FT)	74233.	45858.	45077.
DIA. (IN)	3.84	3.10	3.10
TIP SPEED	2097.	1693.	1692.
VOL. FLOW	759.	488.	481.
HEAD COEF	0.543	0.515	0.506
FLOW COEF	0.095		
DIAMETER RATIO	0.328		
BEARING DN	3.00E+06		
SHAFT DIAMETER	24.00		

*** O2 BOOST TURBINE ***

EFFICIENCY (T/T)	0.875
EFFICIENCY (T/S)	0.790
SPEED (RPM)	11043.
MEAN DIA (IN)	5.11
EFF AREA (IN2)	2.75
U/C (ACTUAL)	0.553
MAX TIP SPEED	271.
STAGES	1
GAMMA	1.40
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	26.
EXIT MACH NUMBER	0.03
SPECIFIC SPEED	67.53
SPECIFIC DIAMETER	1.23

*** O2 BOOST PUMP ***

EFFICIENCY	0.764
HORSEPOWER	26.
SPEED (RPM)	11043.
S SPEED	3026.
HEAD (FT)	242.
DIA. (IN)	2.73
TIP SPEED	132.
VOL. FLOW	283.
HEAD COEF	0.454
FLOW COEF	0.200

*** O2 TURBINE ***

EFFICIENCY (T/T)	0.859
EFFICIENCY (T/S)	0.829
SPEED (RPM)	68164.
HORSEPOWER	594.
MEAN DIA (IN)	2.77
EFF AREA (IN2)	0.32
U/C (ACTUAL)	0.547
MAX TIP SPEED	883.
STAGES	2
GAMMA	1.40
PRESS RATIO (T/T)	1.13
PRESS RATIO (T/S)	1.13
EXIT MACH NUMBER	0.07
SPECIFIC SPEED	50.63
SPECIFIC DIAMETER	1.58

*** O2 PUMP ***

EFFICIENCY	0.747
HORSEPOWER	594.
SPEED (RPM)	68164.
SS SPEED	22656.
S SPEED	1800.
HEAD (FT)	5458.
DIA. (IN)	2.16
TIP SPEED	642.
VOL. FLOW	281.
HEAD COEF	0.426
FLOW COEF	0.153
DIAMETER RATIO	0.681
BEARING DN	1.36E+06
SHAFT DIAMETER	20.00

TABLE A-1. — OPTIMIZED SPLIT EXPANDER (CONTINUED)

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***********************************
* CHAMBER & NOZZLE HEAT TRANSFER  *
***********************************

      ** CHAMBER DESIGN **

CHAMBER MATL/TYPE             COPPER/TUBULAR
WDA (LBM/SEC), CHAMBER FLOW         4.85
DPIN (PSID), INLET DELTA P         49.15
DP   (PSID), CHAMBER DELTA P      205.74
DPEX (PSID), EXIT DELTA P          98.23
DPT  (PSID), TOTAL DELTA P        353.11
QTOT (BTU/S), HEAT TRANSFER     10710.84
DTCH (R), DELTA-TEMPERATURE       578.32
UTTM, ULTIMATE TEMP MARGIN        154.75
PRYS, MAX STRESS RATIO             58.20
THOT, MAX HOT WALL TEMPERATURE   1431.53
UTTS, THROAT MAX TEMPERATURE     1127.50
ASP,  ASPECT RATIO                  3.00
ZI (IN), CHAMBER LENGTH            15.25
ARI, CONTRACTION RATIO              3.00
TN, NUMBER OF TUBES               120.00
```

TABLE A-2. — OPTIMIZED FULL EXPANDER WITH REGENERATOR

ENGINE PERFORMANCE PARAMETERS

CHAMBER PRESSURE	2150.9
VAC ENGINE THRUST	25000.
TURBINE PRESSURE RATIO	2.250
TOTAL ENGINE FLOW RATE	52.07
DEL. VAC. ISP	480.1
THROAT AREA	5.69
NOZZLE AREA RATIO	1000.0
NOZZLE EXIT DIAMETER	85.15
ENGINE MIXTURE RATIO	6.00
ETA C*	0.993
CHAMBER COOLANT DP	856.
CHAMBER COOLANT DT	584.
NOZZLE/CHAMBER Q	16189.

ENGINE STATION CONDITIONS

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	18.6	37.4	7.45	-107.5	4.37
B.P. EXIT	100.8	38.5	7.45	-103.0	4.39
PUMP INLET	100.8	38.5	7.45	-103.0	4.39
1ST STAGE EXIT	2333.0	70.6	7.45	38.7	4.41
2ND STAGE EXIT	4552.2	101.1	7.45	178.1	4.48
PUMP EXIT	6776.6	129.7	7.45	315.5	4.57
COLD REGEN IN	6708.8	130.2	7.45	315.5	4.55
COLD REGEN EX	6641.7	294.7	7.45	949.6	2.83
COOLANT INLET	6641.7	294.7	7.45	949.6	2.83
COOLANT EXIT	5785.6	878.6	7.45	3123.7	1.06
TBV INLET	5727.7	878.9	0.37	3123.7	1.06
TBV EXIT	2482.7	899.6	0.37	3123.7	0.49
O2 TRB INLET	5727.7	878.9	7.07	3123.7	1.06
O2 TRB EXIT	5177.8	861.4	7.07	3050.2	0.98
H2 TRB INLET	5177.8	861.4	7.07	3050.2	0.98
H2 TRB EXIT	2632.7	753.4	7.07	2609.5	0.61
H2 TRB DIFFUSER	2592.7	753.6	7.07	2609.5	0.60
H2 BST TRB IN	2566.7	753.6	7.07	2609.5	0.60
H2 BST TRB OUT	2546.6	752.6	7.07	2604.7	0.59
H2 BST TRB DIFF	2531.9	752.7	7.07	2604.7	0.59
O2 BST TRB IN	2506.6	752.8	7.07	2604.7	0.58
O2 BST TRB OUT	2496.6	752.2	7.07	2602.2	0.58
O2 BST TRB DIFF	2495.2	752.2	7.07	2602.2	0.58
H2 TANK PRESS	18.6	774.5	0.0077	2628.2	0.0045
GOX HEAT EXCH IN	2482.7	759.6	7.44	2628.2	0.57
GOX HEAT EXCH OUT	2470.3	759.3	7.44	2626.9	0.57
HOT REGEN IN	2470.3	759.3	7.44	2626.9	0.57
HOT REGEN EX	2396.2	581.5	7.44	1992.2	0.71
FSOV INLET	2396.2	581.5	7.44	1992.2	0.71
FSOV EXIT	2336.3	581.8	7.44	1992.2	0.69
CHAMBER INJ	2312.9	581.9	7.44	1992.2	0.68
CHAMBER	2150.9				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	16.0	162.7	44.7	61.9	70.99
B.P. EXIT	135.2	165.3	44.7	62.3	70.84
PUMP INLET	135.2	165.3	44.7	62.3	70.84
PUMP EXIT	3483.5	181.0	44.7	74.0	71.48
O2 TANK PRESS	16.0	400.0	0.076	204.7	0.12
OSOV INLET	3448.7	181.2	6.7	74.0	71.43
OSOV EXIT	2414.1	185.3	6.7	74.0	69.85
OCV INLET	3448.7	181.2	37.9	74.0	71.43
OCV EXIT	2414.1	185.3	37.9	74.0	69.85
CHAMBER INJ	2389.9	185.4	44.6	74.0	69.81
CHAMBER	2150.9				

* VALVE DATA *

VALVE	DELTA P	AREA	FLOW	% BYPASS
TBV	3245.	0.01	0.37	5.00
FSOV	60.	1.66	7.44	
OCV	1035.	0.21	44.63	

* INJECTOR DATA *

INJECTOR	DELTA P	AREA	FLOW
FUEL	162.	1.05	7.44
LOX	239.	0.52	44.63

TABLE A-2. — OPTIMIZED FULL EXPANDER WITH REGENERATOR (CONTINUED)

TURBOMACHINERY PERFORMANCE DATA

H2 BOOST TURBINE

EFFICIENCY	(T/T)	0.815
EFFICIENCY	(T/S)	0.413
SPEED	(RPM)	41350.
MEAN DIA	(IN)	1.44
EFF AREA	(IN2)	2.96
U/C	(ACTUAL)	0.531
MAX TIP SPEED		380.
STAGES		1
GAMMA		1.42
PRESS RATIO	(T/T)	1.01
PRESS RATIO	(T/S)	1.02
HORSEPOWER		48.
EXIT MACH NUMBER		0.09
SPECIFIC SPEED		149.69
SPECIFIC DIAMETER		0.51

H2 BOOST PUMP

EFFICIENCY		0.765
HORSEPOWER		48.
SPEED	(RPM)	41350.
S SPEED		3045.
HEAD	(FT)	2701.
DIA.	(IN)	2.43
TIP SPEED		439.
VOL. FLOW		761.
HEAD COEF		0.450
FLOW COEF		0.201

H2 TURBINE

EFFICIENCY	(T/T)	0.847
EFFICIENCY	(T/S)	0.825
SPEED	(RPM)	125000.
HORSEPOWER		4411.
MEAN DIA.	(IN)	3.29
EFF AREA	(IN2)	0.28
U/C	(ACTUAL)	0.540
MAX TIP SPEED		1887.
STAGES		2
GAMMA		1.42
PRESS RATIO	(T/T)	1.97
PRESS RATIO	(T/S)	2.01
EXIT MACH NUMBER		0.16
SPECIFIC SPEED		40.66
SPECIFIC DIAMETER		1.91

H2 PUMP

	STAGE ONE	STAGE TWO	STAGE THREE
EFFICIENCY	0.661	0.662	0.662
HORSEPOWER	1493.	1469.	1448.
SPEED (RPM)	125000.	125000.	125000.
SS SPEED	11320.		
S SPEED	775.	778.	779.
HEAD (FT)	72927.	71837.	70760.
DIA. (IN)	3.81	3.81	3.81
TIP SPEED	2080.	2080.	2081.
VOL. FLOW	757.	747.	731.
HEAD COEF	0.542	0.534	0.526
FLOW COEF	0.095		
DIAMETER RATIO	0.331		
BEARING DN	3.00E+06		
SHAFT DIAMETER	24.00		

O2 BOOST TURBINE

EFFICIENCY	(T/T)	0.877
EFFICIENCY	(T/S)	0.732
SPEED	(RPM)	11044.
MEAN DIA	(IN)	4.11
EFF AREA	(IN2)	4.26
U/C	(ACTUAL)	0.552
MAX TIP SPEED		234.
STAGES		1
GAMMA		1.42
PRESS RATIO	(T/T)	1.00
PRESS RATIO	(T/S)	1.00
HORSEPOWER		26.
EXIT MACH NUMBER		0.03
SPECIFIC SPEED		98.26
SPECIFIC DIAMETER		0.87

O2 BOOST PUMP

EFFICIENCY		0.764
HORSEPOWER		26.
SPEED	(RPM)	11044.
S SPEED		3026.
HEAD	(FT)	242.
DIA.	(IN)	2.73
TIP SPEED		132.
VOL. FLOW		283.
HEAD COEF		0.450
FLOW COEF		0.200

O2 TURBINE

EFFICIENCY	(T/T)	0.854
EFFICIENCY	(T/S)	0.806
SPEED	(RPM)	73500.
HORSEPOWER		736.
MEAN DIA	(IN)	3.29
EFF AREA	(IN2)	0.43
U/C	(ACTUAL)	0.550
MAX TIP SPEED		1111.
STAGES		1
GAMMA		1.42
PRESS RATIO	(T/T)	1.11
PRESS RATIO	(T/S)	1.11
EXIT MACH NUMBER		0.09
SPECIFIC SPEED		42.28
SPECIFIC DIAMETER		1.88

O2 PUMP

EFFICIENCY		0.745
HORSEPOWER		736.
SPEED	(RPM)	73500.
SS SPEED		24428.
S SPEED		1655.
HEAD	(FT)	6743.
DIA.	(IN)	2.19
TIP SPEED		702.
VOL. FLOW		281.
HEAD COEF		0.440
FLOW COEF		0.147
DIAMETER RATIO		0.677
BEARING DN		1.47E+06
SHAFT DIAMETER		20.00

REGENERATOR DATA

	COLD SIDE	HOT SIDE
DELP	67.09	74.11
DELT	164.49	-177.83
AREA	0.44	1.68
FLOW	7.45	7.44
EFFECTIVENESS	0.28	
NTU	0.41	
CRATIO	0.92	
CMIN	26.55	
REGEN Q	4720.98	

TABLE A-2. — OPTIMIZED FULL EXPANDER WITH REGENERATOR (CONTINUED)

** CHAMBER DESIGN **

CHAMBER MATL/TYPE	COPPER/TUBULAR
CASE NUMBER	1.0
WDA (LBM/SEC), CHAMBER FLOW	7.45
DPIN (PSID), INLET DELTA P	152.77
DP (PSID), CHAMBER DELTA P	442.15
DPEX (PSID), EXIT DELTA P	160.11
DPT (PSID), TOTAL DELTA P	755.02
QTOT (BTU/S), HEAT TRANSFER	12410.55
DTCH (R), DELTA TEMPERATURE	440.84
UTTM, ULTIMATE TEMP MARGIN	100.82
PRYS, MAX STRESS RATIO	78.57
THOT, MAX HOT WALL TEMPERATURE	1430.15
UTTS, THROAT MAX TEMPERATURE	1401.49
ASP, ASPECT RATIO	3.00
ZI (IN), CHAMBER LENGTH	18.00
ARI, CONTRACTION RATIO	5.40
TN, NUMBER OF TUBES	100.00

TABLE A-3. — SPLIT EXPANDER—35-PERCENT JACKET BYPASS/30-PERCENT ENHANCEMENT

ENGINE PERFORMANCE PARAMETERS

CHAMBER PRESSURE	1758.1
VAC ENGINE THRUST	25000.
TURBINE PRESSURE RATIO	1.96
TOTAL ENGINE FLOW RATE	52.08
DEL. VAC. ISP	480.1
THROAT AREA	6.96
NOZZLE AREA RATIO	1000.0
NOZZLE EXIT DIAMETER	94.12
ENGINE MIXTURE RATIO	6.00
ETA C*	0.993
CHAMBER COOLANT DP	622.
CHAMBER COOLANT DT	883.
NOZZLE/CHAMBER Q	15894.

ENGINE STATION CONDITIONS

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	18.6	37.4	7.45	-107.5	4.37
B.P. EXIT	100.5	38.5	7.45	-103.0	4.39
PUMP INLET	100.5	38.5	7.45	-103.0	4.39
1ST STAGE EXIT	2374.9	71.6	7.45	42.3	4.41
JBV INLET	2327.4	72.0	2.60	42.3	4.38
JBV EXIT	1978.3	74.7	2.60	42.3	4.15
2ND STAGE EXIT	3622.9	87.5	4.85	117.3	4.47
PUMP EXIT	4871.2	102.9	4.85	191.3	4.53
COOLANT INLET	4822.5	103.4	4.85	191.3	4.51
COOLANT EXIT	4200.5	986.4	4.85	3468.4	0.72
TBV INLET	4158.5	986.7	0.24	3468.4	0.72
TBV EXIT	2072.2	1001.1	0.24	3468.4	0.37
O2 TRB INLET	4158.5	986.7	4.61	3468.4	0.72
O2 TRB EXIT	3723.2	963.6	4.61	3377.1	0.66
H2 TRB INLET	3723.2	963.6	4.61	3377.1	0.66
H2 TRB EXIT	2191.4	862.1	4.61	2985.4	0.45
H2 TRB DIFFUSER	2165.8	862.3	4.61	2985.4	0.44
H2 BST TRB IN	2144.2	862.3	4.61	2985.4	0.44
H2 BST TRB OUT	2122.8	860.5	4.61	2978.1	0.44
H2 BST TRB DIFF	2115.9	860.6	4.61	2978.1	0.44
O2 BST TRB IN	2094.7	860.7	4.61	2978.1	0.43
O2 BST TRB OUT	2083.6	859.6	4.61	2974.2	0.43
O2 BST TRB DIFF	2082.6	859.7	4.61	2974.2	0.43
H2 TANK PRESS	18.6	880.1	0.0068	2998.9	0.0040
GOX HEAT EXCH IN	2072.2	866.7	4.84	2998.9	0.42
GOX HEAT EXCH OUT	2061.9	866.2	4.84	2996.8	0.42
MIXER HOT IN	2061.9	866.2	4.84	2996.8	0.42
MIXER COLD IN	1978.3	74.7	2.60	42.3	4.15
MIXER OUT	1958.8	576.3	7.44	1965.7	0.59
FSOV INLET	1958.8	576.3	7.44	1965.7	0.59
FSOV EXIT	1909.8	576.6	7.44	1965.7	0.58
CHAMBER INJ	1890.7	576.7	7.44	1965.7	0.57
CHAMBER	1758.1				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	16.0	162.7	44.7	61.9	70.99
B.P. EXIT	135.2	165.3	44.7	62.3	70.84
PUMP INLET	135.2	165.3	44.7	62.3	70.84
PUMP EXIT	2847.4	178.0	44.7	71.7	71.39
O2 TANK PRESS	16.0	400.0	0.076	204.7	0.12
OSOV INLET	2818.9	178.2	6.7	71.7	71.34
OSOV EXIT	1973.2	181.5	6.7	71.7	70.02
OCV INLET	2818.9	178.2	37.9	71.7	71.34
OCV EXIT	1973.2	181.5	37.9	71.7	70.02
CHAMBER INJ	1953.5	181.5	44.6	71.7	69.99
CHAMBER	1758.1				

* VALVE DATA *

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	349.	0.10	2.60	34.87
TBV	2086.	0.01	0.24	5.00
FSOV	49.	2.02	7.44	
OCV	846.	0.23	44.64	

* INJECTOR DATA *

INJECTOR	DELTA P	AREA	FLOW
FUEL	133.	1.28	7.44
LOX	195.	0.57	44.64

TABLE A-3. — SPLIT EXPANDER—35-PERCENT JACKET BYPASS/30-PERCENT ENHANCEMENT (CONTINUED)

TURBOMACHINERY PERFORMANCE DATA

H2 BOOST TURBINE

EFFICIENCY (T/T)	0.861
EFFICIENCY (T/S)	0.599
SPEED (RPM)	41262.
MEAN DIA (IN)	1.86
EFF AREA (IN2)	2.20
U/C (ACTUAL)	0.553
MAX TIP SPEED	437.
STAGES	1
GAMMA	1.42
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	48.
EXIT MACH NUMBER	0.07
SPECIFIC SPEED	135.63
SPECIFIC DIAMETER	0.63

H2 BOOST PUMP

EFFICIENCY	0.766
HORSEPOWER	48.
SPEED (RPM)	41262.
S SPEED	3049.
HEAD (FT)	2689.
DIA. (IN)	2.43
TIP SPEED	438.
VOL. FLOW	761.
HEAD COEF	0.450
FLOW COEF	0.201

H2 TURBINE

EFFICIENCY (T/T)	0.842
EFFICIENCY (T/S)	0.819
SPEED (RPM)	125000.
HORSEPOWER	2553.
MEAN DIA. (IN)	2.79
EFF AREA (IN2)	0.27
U/C (ACTUAL)	0.486
MAX TIP SPEED	1620.
STAGES	2
GAMMA	1.42
PRESS RATIO (T/T)	1.70
PRESS RATIO (T/S)	1.73
EXIT MACH NUMBER	0.13
SPECIFIC SPEED	41.78
SPECIFIC DIAMETER	1.68

H2 PUMP

	STAGE ONE	STAGE TWO	STAGE THREE
EFFICIENCY	0.658	0.695	0.694
HORSEPOWER	1531.	515.	508.
SPEED (RPM)	125000.	125000.	125000.
SS SPEED	11356.		
S SPEED	764.	967.	970.
HEAD (FT)	74401.	40492.	39952.
DIA. (IN)	3.84	2.94	2.94
TIP SPEED	2099.	1603.	1603.
VOL. FLOW	759.	487.	481.
HEAD COEF	0.543	0.507	0.500
FLOW COEF	0.094		
DIAMETER RATIO	0.328		
BEARING DN	3.00E+06		
SHAFT DIAMETER	24.00		

O2 BOOST TURBINE

EFFICIENCY (T/T)	0.876
EFFICIENCY (T/S)	0.785
SPEED (RPM)	11043.
MEAN DIA (IN)	5.11
EFF AREA (IN2)	3.06
U/C (ACTUAL)	0.553
MAX TIP SPEED	273.
STAGES	1
GAMMA	1.42
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	26.
EXIT MACH NUMBER	0.03
SPECIFIC SPEED	70.95
SPECIFIC DIAMETER	1.17

O2 BOOST PUMP

EFFICIENCY	0.764
HORSEPOWER	26.
SPEED (RPM)	11043.
S SPEED	3026.
HEAD (FT)	242.
DIA. (IN)	2.73
TIP SPEED	132.
VOL. FLOW	283.
HEAD COEF	0.450
FLOW COEF	0.200

O2 TURBINE

EFFICIENCY (T/T)	0.863
EFFICIENCY (T/S)	0.829
SPEED (RPM)	68217.
HORSEPOWER	595.
MEAN DIA (IN)	2.79
EFF AREA (IN2)	0.39
U/C (ACTUAL)	0.550
MAX TIP SPEED	896.
STAGES	2
GAMMA	1.42
PRESS RATIO (T/T)	1.12
PRESS RATIO (T/S)	1.12
EXIT MACH NUMBER	0.07
SPECIFIC SPEED	55.71
SPECIFIC DIAMETER	1.45

O2 PUMP

EFFICIENCY	0.747
HORSEPOWER	595.
SPEED (RPM)	68217.
SS SPEED	22675.
S SPEED	1799.
HEAD (FT)	5469.
DIA. (IN)	2.16
TIP SPEED	643.
VOL. FLOW	281.
HEAD COEF	0.426
FLOW COEF	0.153
DIAMETER RATIO	0.681
BEARING DN	1.36E+06
SHAFT DIAMETER	20.00

TABLE A-4. — FULL EXPANDER WITH REGENERATOR—30-PERCENT ENHANCEMENT

ENGINE PERFORMANCE PARAMETERS

****

CHAMBER PRESSURE	2144.3
VAC ENGINE THRUST	25000.
TURBINE PRESSURE RATIO	2.200
TOTAL ENGINE FLOW RATE	52.07
DEL. VAC. ISP	480.1
THROAT AREA	5.71
NOZZLE AREA RATIO	1000.0
NOZZLE EXIT DIAMETER	85.28
ENGINE MIXTURE RATIO	6.00
ETA C*	0.993
CHAMBER COOLANT DP	1119.
CHAMBER COOLANT DT	619.
NOZZLE/CHAMBER Q	17078.

ENGINE STATION CONDITIONS

****

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	18.6	37.4	7.45	-107.5	4.37
B.P. EXIT	100.2	38.5	7.45	-103.0	4.39
PUMP INLET	100.2	38.5	7.45	-103.0	4.39
1ST STAGE EXIT	2375.0	71.6	7.45	42.3	4.41
2ND STAGE EXIT	4633.0	102.8	7.45	185.0	4.47
PUMP EXIT	6895.5	132.1	7.45	325.7	4.56
COLD REGEN IN	6826.5	132.6	7.45	325.7	4.54
COLD REGEN EX	6758.3	294.7	7.45	951.8	2.86
COOLANT INLET	6758.3	294.7	7.45	951.8	2.86
COOLANT EXIT	5639.1	913.9	7.45	3245.4	1.01
TBV INLET	5582.7	914.3	0.37	3245.4	1.00
TBV EXIT	2474.5	934.5	0.37	3245.4	0.47
O2 TRB INLET	5582.7	914.3	7.07	3245.4	1.00
O2 TRB EXIT	5070.1	896.5	7.07	3172.1	0.93
H2 TRB INLET	5070.1	896.5	7.07	3172.1	0.93
H2 TRB EXIT	2621.1	784.8	7.07	2720.7	0.58
H2 TRB DIFFUSER	2583.0	785.0	7.07	2720.7	0.57
H2 BST TRB IN	2557.2	785.0	7.07	2720.7	0.57
H2 BST TRB OUT	2537.9	784.0	7.07	2716.0	0.57
H2 BST TRB DIFF	2523.1	784.1	7.07	2716.0	0.56
O2 BST TRB IN	2497.9	784.2	7.07	2716.0	0.56
O2 BST TRB OUT	2488.4	783.6	7.07	2713.4	0.56
O2 BST TRB DIFF	2487.0	783.6	7.07	2713.4	0.56
H2 TANK PRESS	18.6	806.4	0.0074	2740.0	0.0044
GOX HEAT EXCH IN	2474.5	791.1	7.44	2740.0	0.55
GOX HEAT EXCH OUT	2462.2	790.8	7.44	2738.7	0.55
HOT REGEN IN	2462.2	790.8	7.44	2738.7	0.55
HOT REGEN EX	2388.3	614.6	7.44	2111.9	0.67
FSOV INLET	2388.3	614.6	7.44	2111.9	0.67
FSOV EXIT	2328.6	614.9	7.44	2111.9	0.66
CHAMBER INJ	2305.3	615.0	7.44	2111.9	0.65
CHAMBER	2144.3				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	16.0	162.7	44.7	61.9	70.99
B.P. EXIT	135.2	165.3	44.7	62.3	70.84
PUMP INLET	135.2	165.3	44.7	62.3	70.84
PUMP EXIT	3472.7	181.0	44.7	73.9	71.48
O2 TANK PRESS	16.0	400.0	0.076	204.7	0.12
OSOV INLET	3438.0	181.1	6.7	73.9	71.43
OSOV EXIT	2406.6	185.3	6.7	73.9	69.85
OCV INLET	3438.0	181.1	37.9	73.9	71.43
OCV EXIT	2406.6	185.3	37.9	73.9	69.85
CHAMBER INJ	2382.5	185.4	44.6	73.9	69.82
CHAMBER	2144.3				

* VALVE DATA *

VALVE	DELTA P	AREA	FLOW	% BYPASS
TBV	3108.	0.01	0.37	5.00
FSOV	60.	1.71	7.44	
OCV	1031.	0.21	44.63	

* INJECTOR DATA *

INJECTOR	DELTA P	AREA	FLOW
FUEL	161.	1.09	7.44
LOX	238.	0.52	44.63

TABLE A-4. — FULL EXPANDER WITH REGENERATOR—30-PERCENT ENHANCEMENT (CONTINUED)

*** TURBOMACHINERY PERFORMANCE DATA ***

*** H2 BOOST TURBINE ***

EFFICIENCY (T/T)	0.811
EFFICIENCY (T/S)	0.400
SPEED (RPM)	41201.
MEAN DIA (IN)	1.44
EFF AREA (IN2)	3.10
U/C (ACTUAL)	0.532
MAX TIP SPEED	381.
STAGES	1
GAMMA	1.37
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.02
HORSEPOWER	47.
EXIT MACH NUMBER	0.10
SPECIFIC SPEED	149.84
SPECIFIC DIAMETER	0.51

*** H2 BOOST PUMP ***

EFFICIENCY	0.766
HORSEPOWER	47.
SPEED (RPM)	41201.
S SPEED	3052.
HEAD (FT)	2680.
DIA. (IN)	2.43
TIP SPEED	438.
VOL. FLOW	761.
HEAD COEF	0.450
FLOW COEF	0.201

*** H2 TURBINE ***

EFFICIENCY (T/T)	0.847
EFFICIENCY (T/S)	0.825
SPEED (RPM)	125000.
HORSEPOWER	4518.
MEAN DIA. (IN)	3.29
EFF AREA (IN2)	0.30
U/C (ACTUAL)	0.533
MAX TIP SPEED	1890.
STAGES	2
GAMMA	1.37
PRESS RATIO (T/T)	1.93
PRESS RATIO (T/S)	1.97
EXIT MACH NUMBER	0.15
SPECIFIC SPEED	41.14
SPECIFIC DIAMETER	1.86

*** H2 PUMP ***

	STAGE ONE	STAGE TWO	STAGE THREE
EFFICIENCY	0.658	0.659	0.659
HORSEPOWER	1531.	1505.	1482.
SPEED (RPM)	125000.	125000.	125000.
SS SPEED	11382.		
S SPEED	764.	768.	769.
HEAD (FT)	74412.	73235.	72098.
DIA. (IN)	3.85	3.84	3.85
TIP SPEED	2099.	2098.	2099.
VOL. FLOW	759.	748.	732.
HEAD COEF	0.543	0.535	0.527
FLOW COEF	0.094		
DIAMETER RATIO	0.328		
BEARING DN	3.00E+06		
SHAFT DIAMETER	24.00		

*** O2 BOOST TURBINE ***

EFFICIENCY (T/T)	0.876
EFFICIENCY (T/S)	0.727
SPEED (RPM)	11044.
MEAN DIA (IN)	4.11
EFF AREA (IN2)	4.45
U/C (ACTUAL)	0.552
MAX TIP SPEED	235.
STAGES	1
GAMMA	1.37
PRESS RATIO (T/T)	1.00
PRESS RATIO (T/S)	1.00
HORSEPOWER	26.
EXIT MACH NUMBER	0.03
SPECIFIC SPEED	100.00
SPECIFIC DIAMETER	0.85

*** O2 BOOST PUMP ***

EFFICIENCY	0.764
HORSEPOWER	26.
SPEED (RPM)	11044.
S SPEED	3026.
HEAD (FT)	242.
DIA. (IN)	2.73
TIP SPEED	132.
VOL. FLOW	283.
HEAD COEF	0.450
FLOW COEF	0.200

*** O2 TURBINE ***

EFFICIENCY (T/T)	0.857
EFFICIENCY (T/S)	0.807
SPEED (RPM)	73416.
HORSEPOWER	734.
MEAN DIA (IN)	3.29
EFF AREA (IN2)	0.46
U/C (ACTUAL)	0.550
MAX TIP SPEED	1111.
STAGES	1
GAMMA	1.37
PRESS RATIO (T/T)	1.10
PRESS RATIO (T/S)	1.11
EXIT MACH NUMBER	0.09
SPECIFIC SPEED	43.72
SPECIFIC DIAMETER	1.82

*** O2 PUMP ***

EFFICIENCY	0.745
HORSEPOWER	734.
SPEED (RPM)	73416.
SS SPEED	24400.
S SPEED	1657.
HEAD (FT)	6721.
DIA. (IN)	2.19
TIP SPEED	701.
VOL. FLOW	281.
HEAD COEF	0.440
FLOW COEF	0.147
DIAMETER RATIO	0.677
BEARING DN	1.47E+06
SHAFT DIAMETER	20.00

REGENERATOR DATA

	COLD SIDE	HOT SIDE
DELP	68.27	73.86
DELT	162.10	-176.30
AREA	0.44	1.72
FLOW	7.45	7.44
EFFECTIVENESS	0.27	
NTU	0.38	
CRATIO	0.92	
CMIN	26.45	
REGEN Q	4662.17	

TABLE A-5. — SPLIT EXPANDER—50-PERCENT JACKET BYPASS/30-PERCENT ENHANCEMENT

ENGINE PERFORMANCE PARAMETERS

CHAMBER PRESSURE	1755.7
VAC ENGINE THRUST	25000.
TURBINE PRESSURE RATIO	2.22
TOTAL ENGINE FLOW RATE	52.08
DEL. VAC. ISP	480.1
THROAT AREA	6.97
NOZZLE AREA RATIO	1000.0
NOZZLE EXIT DIAMETER	94.18
ENGINE MIXTURE RATIO	6.00
ETA C*	0.993
CHAMBER COOLANT DP	539.
CHAMBER COOLANT DT	1010.
NOZZLE/CHAMBER Q	13882.

ENGINE STATION CONDITIONS

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	18.6	37.4	7.45	-107.5	4.37
B.P. EXIT	101.0	38.5	7.45	-103.0	4.39
PUMP INLET	101.0	38.5	7.45	-103.0	4.39
1ST STAGE EXIT	2371.6	71.5	7.45	42.0	4.41
JBV INLET	2324.2	71.9	3.73	42.0	4.38
JBV EXIT	1975.5	74.6	3.73	42.0	4.15
2ND STAGE EXIT	3876.7	94.2	3.72	142.4	4.41
PUMP EXIT	5350.3	115.7	3.72	239.8	4.44
COOLANT INLET	5296.8	116.1	3.72	239.8	4.42
COOLANT EXIT	4758.0	1125.9	3.72	3971.6	0.72
TBV INLET	4710.4	1126.2	0.19	3971.6	0.71
TBV EXIT	2069.7	1145.2	0.19	3971.6	0.32
O2 TRB INLET	4710.4	1126.2	3.53	3971.6	0.71
O2 TRB EXIT	4139.8	1096.5	3.53	3852.8	0.65
H2 TRB INLET	4139.8	1096.5	3.53	3852.8	0.65
H2 TRB EXIT	2188.4	963.3	3.53	3339.2	0.40
H2 TRB DIFFUSER	2166.5	963.4	3.53	3339.2	0.40
H2 BST TRB IN	2144.8	963.4	3.53	3339.2	0.40
H2 BST TRB OUT	2120.1	961.0	3.53	3329.6	0.39
H2 BST TRB DIFF	2115.1	961.0	3.53	3329.6	0.39
O2 BST TRB IN	2094.0	961.2	3.53	3329.6	0.39
O2 BST TRB OUT	2080.9	959.8	3.53	3324.5	0.39
O2 BST TRB DIFF	2080.1	959.8	3.53	3324.5	0.39
H2 TANK PRESS	18.6	983.4	0.0061	3356.8	0.0036
GOX HEAT EXCH IN	2069.7	969.1	3.71	3356.8	0.38
GOX HEAT EXCH OUT	2059.3	968.4	3.71	3354.1	0.38
MIXER HOT IN	2059.3	968.4	3.71	3354.1	0.38
MIXER COLD IN	1975.5	74.6	3.73	42.0	4.15
MIXER OUT	1956.4	502.3	7.44	1695.5	0.68
FSOV INLET	1956.4	502.3	7.44	1695.5	0.68
FSOV EXIT	1907.5	502.5	7.44	1695.5	0.66
CHAMBER INJ	1888.4	502.6	7.44	1695.5	0.65
CHAMBER	1755.7				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	16.0	162.7	44.7	61.9	70.99
B.P. EXIT	135.2	165.3	44.7	62.3	70.84
PUMP INLET	135.2	165.3	44.7	62.3	70.84
PUMP EXIT	2843.4	178.0	44.7	71.7	71.38
O2 TANK PRESS	16.0	400.0	0.076	204.7	0.12
OSOV INLET	2814.9	178.1	6.7	71.7	71.34
OSOV EXIT	1970.4	181.4	6.7	71.7	70.03
OCV INLET	2814.9	178.1	37.9	71.7	71.34
OCV EXIT	1970.4	181.4	37.9	71.7	70.03
CHAMBER INJ	1950.7	181.5	44.6	71.7	69.99
CHAMBER	1755.7				

* VALVE DATA *

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	349.	0.14	3.73	50.04
TBV	2641.	0.01	0.19	5.00
FSOV	49.	1.89	7.44	
OCV	844.	0.23	44.64	

* INJECTOR DATA *

INJECTOR	DELTA P	AREA	FLOW
FUEL	133.	1.20	7.44
LOX	195.	0.57	44.64

TABLE A-5. — SPLIT EXPANDER—50-PERCENT JACKET BYPASS/30-PERCENT ENHANCEMENT (CONTINUED)

TURBOMACHINERY PERFORMANCE DATA

H2 BOOST TURBINE

EFFICIENCY (T/T)	0.873
EFFICIENCY (T/S)	0.687
SPEED (RPM)	41386.
MEAN DIA (IN)	2.12
EFF AREA (IN2)	1.66
U/C (ACTUAL)	0.553
MAX TIP SPEED	469.
STAGES	1
GAMMA	1.42
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	48.
EXIT MACH NUMBER	0.06
SPECIFIC SPEED	113.87
SPECIFIC DIAMETER	0.76

H2 BOOST PUMP

EFFICIENCY	0.765
HORSEPOWER	48.
SPEED (RPM)	41386.
S SPEED	3044.
HEAD (FT)	2706.
DIA. (IN)	2.43
TIP SPEED	440.
VOL. FLOW	761.
HEAD COEF	0.450
FLOW COEF	0.201

H2 TURBINE

EFFICIENCY (T/T)	0.819
EFFICIENCY (T/S)	0.804
SPEED (RPM)	125000.
HORSEPOWER	2568.
MEAN DIA. (IN)	3.11
EFF AREA (IN2)	0.20
U/C (ACTUAL)	0.473
MAX TIP SPEED	1772.
STAGES	2
GAMMA	1.42
PRESS RATIO (T/T)	1.89
PRESS RATIO (T/S)	1.92
EXIT MACH NUMBER	0.12
SPECIFIC SPEED	31.22
SPECIFIC DIAMETER	2.13

H2 PUMP

	STAGE ONE	STAGE TWO	STAGE THREE
EFFICIENCY	0.658	0.629	0.633
HORSEPOWER	1527.	529.	512.
SPEED (RPM)	125000.	125000.	125000.
SS SPEED	11306.		
S SPEED	765.	737.	748.
HEAD (FT)	74265.	49178.	47956.
DIA. (IN)	3.84	3.20	3.20
TIP SPEED	2097.	1745.	1746.
VOL. FLOW	758.	379.	376.
HEAD COEF	0.543	0.519	0.506
FLOW COEF	0.094		
DIAMETER RATIO	0.328		
BEARING DN	3.00E+06		
SHAFT DIAMETER	24.00		

O2 BOOST TURBINE

EFFICIENCY (T/T)	0.868
EFFICIENCY (T/S)	0.803
SPEED (RPM)	11043.
MEAN DIA (IN)	5.83
EFF AREA (IN2)	2.29
U/C (ACTUAL)	0.553
MAX TIP SPEED	302.
STAGES	1
GAMMA	1.42
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	26.
EXIT MACH NUMBER	0.03
SPECIFIC SPEED	54.75
SPECIFIC DIAMETER	1.49

O2 BOOST PUMP

EFFICIENCY	0.764
HORSEPOWER	26.
SPEED (RPM)	11043.
S SPEED	3026.
HEAD (FT)	242.
DIA. (IN)	2.73
TIP SPEED	132.
VOL. FLOW	283.
HEAD COEF	0.450
FLOW COEF	0.200

O2 TURBINE

EFFICIENCY (T/T)	0.846
EFFICIENCY (T/S)	0.823
SPEED (RPM)	68177.
HORSEPOWER	594.
MEAN DIA (IN)	3.11
EFF AREA (IN2)	0.27
U/C (ACTUAL)	0.536
MAX TIP SPEED	973.
STAGES	2
GAMMA	1.42
PRESS RATIO (T/T)	1.14
PRESS RATIO (T/S)	1.14
EXIT MACH NUMBER	0.07
SPECIFIC SPEED	40.57
SPECIFIC DIAMETER	1.90

O2 PUMP

EFFICIENCY	0.747
HORSEPOWER	594.
SPEED (RPM)	68177.
SS SPEED	22660.
S SPEED	1800.
HEAD (FT)	5461.
DIA. (IN)	2.16
TIP SPEED	642.
VOL. FLOW	281.
HEAD COEF	0.426
FLOW COEF	0.153
DIAMETER RATIO	0.681
BEARING DN	1.36E+06
SHAFT DIAMETER	20.00

TABLE A-6. — SPLIT EXPANDER—50-PERCENT JACKET BYPASS/30-PERCENT ENHANCEMENT—150 TUBES

ENGINE PERFORMANCE PARAMETERS

CHAMBER PRESSURE	1757.3
VAC ENGINE THRUST	25000.
TURBINE PRESSURE RATIO	2.22
TOTAL ENGINE FLOW RATE	52.08
DEL. VAC. ISP	480.1
THROAT AREA	6.96
NOZZLE AREA RATIO	1000.0
NOZZLE EXIT DIAMETER	94.14
ENGINE MIXTURE RATIO	6.00
ETA C*	0.993
CHAMBER COOLANT DP	481.
CHAMBER COOLANT DT	1004.
NOZZLE/CHAMBER Q	13814.

ENGINE STATION CONDITIONS

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	18.6	37.4	7.45	-107.5	4.37
B.P. EXIT	100.7	38.5	7.45	-103.0	4.39
PUMP INLET	100.7	38.5	7.45	-103.0	4.39
1ST STAGE EXIT	2373.8	71.5	7.45	42.2	4.41
JBV INLET	2326.3	71.9	3.73	42.2	4.38
JBV EXIT	1977.4	74.7	3.73	42.2	4.15
2ND STAGE EXIT	3849.6	93.6	3.72	140.0	4.41
PUMP EXIT	5296.6	114.5	3.72	235.0	4.45
COOLANT INLET	5243.6	115.0	3.72	235.0	4.42
COOLANT EXIT	4762.4	1119.3	3.72	3948.4	0.72
TBV INLET	4714.7	1119.6	0.19	3948.4	0.71
TBV EXIT	2070.8	1138.5	0.19	3948.4	0.33
O2 TRB INLET	4714.7	1119.6	3.53	3948.4	0.71
O2 TRB EXIT	4139.3	1089.8	3.53	3829.5	0.65
H2 TRB INLET	4139.3	1089.8	3.53	3829.5	0.65
H2 TRB EXIT	2189.6	958.0	3.53	3320.7	0.41
H2 TRB DIFFUSER	2167.8	958.1	3.53	3320.7	0.40
H2 BST TRB IN	2146.1	958.1	3.53	3320.7	0.40
H2 BST TRB OUT	2121.3	955.7	3.53	3311.1	0.40
H2 BST TRB DIFF	2116.4	955.7	3.53	3311.1	0.39
O2 BST TRB IN	2095.2	955.9	3.53	3311.1	0.39
O2 BST TRB OUT	2082.8	954.5	3.53	3306.0	0.39
O2 BST TRB DIFF	2081.2	954.5	3.53	3306.0	0.39
H2 TANK PRESS	18.6	978.0	0.0061	3338.1	0.0036
GOX HEAT EXCH IN	2070.8	963.8	3.71	3338.1	0.38
GOX HEAT EXCH OUT	2060.5	963.1	3.71	3335.4	0.38
MIXER HOT IN	2060.5	963.1	3.71	3335.4	0.38
MIXER COLD IN	1977.4	74.7	3.73	42.2	4.15
MIXER OUT	1957.4	499.7	7.44	1686.2	0.68
FSOV INLET	1957.4	499.7	7.44	1686.2	0.68
FSOV EXIT	1908.5	499.9	7.44	1686.2	0.66
CHAMBER INJ	1889.4	500.0	7.44	1686.2	0.66
CHAMBER	1757.3				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	16.0	162.7	44.7	61.9	70.99
B.P. EXIT	135.2	165.3	44.7	62.3	70.84
PUMP INLET	135.2	165.3	44.7	62.3	70.84
PUMP EXIT	2846.0	178.0	44.7	71.7	71.39
O2 TANK PRESS	16.0	400.0	0.076	204.7	0.12
OSOV INLET	2817.6	178.2	6.7	71.7	71.34
OSOV EXIT	1972.3	181.4	6.7	71.7	70.02
OCV INLET	2817.6	178.2	37.9	71.7	71.34
OCV EXIT	1972.3	181.4	37.9	71.7	70.02
CHAMBER INJ	1952.6	181.5	44.6	71.7	69.99
CHAMBER	1757.3				

* VALVE DATA *

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	349.	0.14	3.73	50.04
TBV	2644.	0.01	0.19	5.00
FSOV	49.	1.88	7.44	
OCV	845.	0.23	44.64	

* INJECTOR DATA *

INJECTOR	DELTA P	AREA	FLOW
FUEL	132.	1.20	7.44
LOX	195.	0.57	44.64

TABLE A-6. — SPLIT EXPANDER—50-PERCENT JACKET BYPASS/30-PERCENT ENHANCEMENT—150 TUBES (CONTINUED)

TURBOMACHINERY PERFORMANCE DATA

H2 BOOST TURBINE

EFFICIENCY (T/T)	0.873
EFFICIENCY (T/S)	0.688
SPEED (RPM)	41311.
MEAN DIA (IN)	2.12
EFF AREA (IN2)	1.65
U/C (ACTUAL)	0.553
MAX TIP SPEED	468.
STAGES	1
GAMMA	1.45
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	48.
EXIT MACH NUMBER	0.06
SPECIFIC SPEED	113.72
SPECIFIC DIAMETER	0.76

H2 BOOST PUMP

EFFICIENCY	0.766
HORSEPOWER	48.
SPEED (RPM)	41311.
S SPEED	3047.
HEAD (FT)	2695.
DIA. (IN)	2.43
TIP SPEED	439.
VOL. FLOW	761.
HEAD COEF	0.450
FLOW COEF	0.201

H2 TURBINE

EFFICIENCY (T/T)	0.820
EFFICIENCY (T/S)	0.805
SPEED (RPM)	125000.
HORSEPOWER	2544.
MEAN DIA. (IN)	3.11
EFF AREA (IN2)	0.20
U/C (ACTUAL)	0.475
MAX TIP SPEED	1771.
STAGES	2
GAMMA	1.45
PRESS RATIO (T/T)	1.89
PRESS RATIO (T/S)	1.92
EXIT MACH NUMBER	0.12
SPECIFIC SPEED	31.27
SPECIFIC DIAMETER	2.14

H2 PUMP

	STAGE ONE	STAGE TWO	STAGE THREE
EFFICIENCY	0.658	0.633	0.636
HORSEPOWER	1529.	515.	500.
SPEED (RPM)	125000.	125000.	125000.
SS SPEED	11337.		
S SPEED	765.	748.	758.
HEAD (FT)	74353.	48203.	47039.
DIA. (IN)	3.84	3.17	3.17
TIP SPEED	2098.	1729.	1730.
VOL. FLOW	758.	379.	376.
HEAD COEF	0.543	0.519	0.506
FLOW COEF	0.094		
DIAMETER RATIO	0.328		
BEARING DN	3.00E+06		
SHAFT DIAMETER	24.80		

O2 BOOST TURBINE

EFFICIENCY (T/T)	0.868
EFFICIENCY (T/S)	0.803
SPEED (RPM)	11043.
MEAN DIA (IN)	5.83
EFF AREA (IN2)	2.28
U/C (ACTUAL)	0.553
MAX TIP SPEED	302.
STAGES	1
GAMMA	1.45
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	26.
EXIT MACH NUMBER	0.02
SPECIFIC SPEED	54.59
SPECIFIC DIAMETER	1.49

O2 BOOST PUMP

EFFICIENCY	0.764
HORSEPOWER	26.
SPEED (RPM)	11043.
S SPEED	3026.
HEAD (FT)	242.
DIA. (IN)	2.73
TIP SPEED	132.
VOL. FLOW	283.
HEAD COEF	0.450
FLOW COEF	0.200

O2 TURBINE

EFFICIENCY (T/T)	0.845
EFFICIENCY (T/S)	0.823
SPEED (RPM)	68204.
HORSEPOWER	595.
MEAN DIA (IN)	3.11
EFF AREA (IN2)	0.27
U/C (ACTUAL)	0.536
MAX TIP SPEED	973.
STAGES	2
GAMMA	1.45
PRESS RATIO (T/T)	1.14
PRESS RATIO (T/S)	1.14
EXIT MACH NUMBER	0.07
SPECIFIC SPEED	40.41
SPECIFIC DIAMETER	1.90

O2 PUMP

EFFICIENCY	0.747
HORSEPOWER	595.
SPEED (RPM)	68204.
SS SPEED	22669.
S SPEED	1799.
HEAD (FT)	5466.
DIA. (IN)	2.16
TIP SPEED	642.
VOL. FLOW	281.
HEAD COEF	0.426
FLOW COEF	0.153
DIAMETER RATIO	0.681
BEARING DN	1.36E+06
SHAFT DIAMETER	20.00

TABLE A-7. — SPLIT EXPANDER—50-PERCENT JACKET BYPASS/30-PERCENT ENHANCEMENT—OPTIMUM TUBE GEOMETRY

ENGINE PERFORMANCE PARAMETERS

CHAMBER PRESSURE	1758.7
VAC ENGINE THRUST	25000.
TURBINE PRESSURE RATIO	2.26
TOTAL ENGINE FLOW RATE	52.08
DEL. VAC. ISP	480.1
THROAT AREA	6.95
NOZZLE AREA RATIO	1000.0
NOZZLE EXIT DIAMETER	94.10
ENGINE MIXTURE RATIO	6.00
ETA C*	0.993
CHAMBER COOLANT DP	388.
CHAMBER COOLANT DT	982.
NOZZLE/CHAMBER Q	13529.

ENGINE STATION CONDITIONS

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	18.6	37.4	7.45	-107.5	4.37
B.P. EXIT	100.5	38.5	7.45	-103.0	4.39
PUMP INLET	100.5	38.5	7.45	-103.0	4.39
1ST STAGE EXIT	2375.6	71.6	7.45	42.3	4.41
JBV INLET	2328.1	72.0	3.73	42.3	4.38
JBV EXIT	1978.9	74.7	3.73	42.3	4.15
2ND STAGE EXIT	3849.3	93.6	3.72	140.0	4.41
PUMP EXIT	5293.1	114.5	3.72	234.7	4.45
COOLANT INLET	5240.1	114.9	3.72	234.7	4.43
COOLANT EXIT	4851.7	1096.9	3.72	3871.6	0.75
TBV INLET	4803.2	1097.1	0.19	3871.6	0.74
TBV EXIT	2072.5	1116.5	0.19	3871.6	0.33
O2 TRB INLET	4803.2	1097.1	3.53	3871.6	0.74
O2 TRB EXIT	4204.3	1067.4	3.53	3752.5	0.67
H2 TRB INLET	4204.3	1067.4	3.53	3752.5	0.67
H2 TRB EXIT	2192.5	935.9	3.53	3243.8	0.42
H2 TRB DIFFUSER	2170.4	936.0	3.53	3243.8	0.41
H2 BST TRB IN	2148.7	936.0	3.53	3243.8	0.41
H2 BST TRB OUT	2123.4	933.6	3.53	3234.3	0.40
H2 BST TRB DIFF	2118.4	933.7	3.53	3234.3	0.40
O2 BST TRB IN	2097.2	933.8	3.53	3234.3	0.40
O2 BST TRB OUT	2083.7	932.4	3.53	3229.1	0.40
O2 BST TRB DIFF	2082.9	932.4	3.53	3229.1	0.40
H2 TANK PRESS	18.6	955.8	0.0062	3261.3	0.0037
GOX HEAT EXCH IN	2072.5	941.7	3.71	3261.3	0.39
GOX HEAT EXCH OUT	2062.1	941.0	3.71	3258.5	0.39
MIXER HOT IN	2062.1	941.0	3.71	3258.5	0.39
MIXER COLD IN	1978.9	74.7	3.73	42.3	4.15
MIXER OUT	1959.0	489.2	7.44	1647.9	0.69
FSOV INLET	1959.0	489.2	7.44	1647.9	0.69
FSOV EXIT	1910.0	489.4	7.44	1647.9	0.68
CHAMBER INJ	1890.9	489.5	7.44	1647.9	0.67
CHAMBER	1758.7				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	16.0	162.7	44.7	61.9	70.99
B.P. EXIT	135.2	165.3	44.7	62.3	70.84
PUMP INLET	135.2	165.3	44.7	62.3	70.84
PUMP EXIT	2848.2	178.1	44.7	71.7	71.39
O2 TANK PRESS	16.0	400.0	0.076	204.7	0.12
OSOV INLET	2819.7	178.2	6.7	71.7	71.34
OSOV EXIT	1973.8	181.5	6.7	71.7	70.02
OCV INLET	2819.7	178.2	37.9	71.7	71.34
OCV EXIT	1973.8	181.5	37.9	71.7	70.02
CHAMBER INJ	1954.1	181.5	44.6	71.7	69.99
CHAMBER	1758.7				

* VALVE DATA *

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	349.	0.14	3.73	50.04
TBV	2731.	0.01	0.19	5.00
FSOV	49.	1.86	7.44	
OCV	846.	0.23	44.64	

* INJECTOR DATA *

INJECTOR	DELTA P	AREA	FLOW
FUEL	132.	1.18	7.44
LOX	195.	0.57	44.64

TABLE A-7. — SPLIT EXPANDER—50-PERCENT JACKET BYPASS/30-PERCENT ENHANCEMENT—OPTIMUM TUBE GEOMETRY (CONTINUED)

TURBOMACHINERY PERFORMANCE DATA

H2 BOOST TURBINE

EFFICIENCY (T/T)	0.873
EFFICIENCY (T/S)	0.691
SPEED (RPM)	41266.
MEAN DIA (IN)	2.12
EFF AREA (IN2)	1.61
U/C (ACTUAL)	0.553
MAX TIP SPEED	466.
STAGES	1
GAMMA	1.43
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.02
HORSEPOWER	48.
EXIT MACH NUMBER	0.06
SPECIFIC SPEED	112.80
SPECIFIC DIAMETER	0.76

H2 BOOST PUMP

EFFICIENCY	0.766
HORSEPOWER	48.
SPEED (RPM)	41266.
S SPEED	3049.
HEAD (FT)	2689.
DIA. (IN)	2.43
TIP SPEED	438.
VOL. FLOW	761.
HEAD COEF	0.450
FLOW COEF	0.201

H2 TURBINE

EFFICIENCY (T/T)	0.819
EFFICIENCY (T/S)	0.803
SPEED (RPM)	125000.
HORSEPOWER	2544.
MEAN DIA. (IN)	3.10
EFF AREA (IN2)	0.19
U/C (ACTUAL)	0.474
MAX TIP SPEED	1766.
STAGES	2
GAMMA	1.43
PRESS RATIO (T/T)	1.92
PRESS RATIO (T/S)	1.94
EXIT MACH NUMBER	0.12
SPECIFIC SPEED	30.92
SPECIFIC DIAMETER	2.16

H2 PUMP

	STAGE ONE	STAGE TWO	STAGE THREE
EFFICIENCY	0.658	0.633	0.637
HORSEPOWER	1531.	514.	499.
SPEED (RPM)	125000.	125000.	125000.
SS SPEED	11355.		
S SPEED	764.	748.	760.
HEAD (FT)	74425.	48132.	46935.
DIA. (IN)	3.85	3.17	3.17
TIP SPEED	2099.	1728.	1728.
VOL. FLOW	759.	379.	376.
HEAD COEF	0.543	0.518	0.506
FLOW COEF	0.094		
DIAMETER RATIO	0.328		
BEARING DN	3.00E+06		
SHAFT DIAMETER	24.00		

O2 BOOST TURBINE

EFFICIENCY (T/T)	0.868
EFFICIENCY (T/S)	0.804
SPEED (RPM)	11043.
MEAN DIA (IN)	5.83
EFF AREA (IN2)	2.22
U/C (ACTUAL)	0.553
MAX TIP SPEED	302.
STAGES	1
GAMMA	1.43
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	26.
EXIT MACH NUMBER	0.03
SPECIFIC SPEED	53.95
SPECIFIC DIAMETER	1.51

O2 BOOST PUMP

EFFICIENCY	0.764
HORSEPOWER	26.
SPEED (RPM)	11043.
S SPEED	3026.
HEAD (FT)	242.
DIA. (IN)	2.73
TIP SPEED	132.
VOL. FLOW	283.
HEAD COEF	0.450
FLOW COEF	0.200

O2 TURBINE

EFFICIENCY (T/T)	0.844
EFFICIENCY (T/S)	0.822
SPEED (RPM)	68227.
HORSEPOWER	595.
MEAN DIA (IN)	3.10
EFF AREA (IN2)	0.26
U/C (ACTUAL)	0.535
MAX TIP SPEED	970.
STAGES	2
GAMMA	1.43
PRESS RATIO (T/T)	1.14
PRESS RATIO (T/S)	1.15
EXIT MACH NUMBER	0.07
SPECIFIC SPEED	39.67
SPECIFIC DIAMETER	1.93

O2 PUMP

EFFICIENCY	0.747
HORSEPOWER	595.
SPEED (RPM)	68227.
SS SPEED	22677.
S SPEED	1798.
HEAD (FT)	5471.
DIA. (IN)	2.16
TIP SPEED	643.
VOL. FLOW	281.
HEAD COEF	0.426
FLOW COEF	0.153
DIAMETER RATIO	0.681
BEARING DN	1.36E+06
SHAFT DIAMETER	20.00

TABLE A-8. — SPLIT EXPANDER—1560°R HOT-WALL TEMPERATURE LIMIT

ENGINE PERFORMANCE PARAMETERS

CHAMBER PRESSURE	1701.4
VAC ENGINE THRUST	25000.
TURBINE PRESSURE RATIO	2.601
TOTAL ENGINE FLOW RATE	52.08
DEL. VAC. ISP	480.1
THROAT AREA	7.19
NOZZLE AREA RATIO	1000.0
NOZZLE EXIT DIAMETER	95.66
ENGINE MIXTURE RATIO	6.00
ETA C*	0.993
CHAMBER COOLANT DP	436.
CHAMBER COOLANT DT	902.
NOZZLE/CHAMBER Q	12498.

ENGINE STATION CONDITIONS

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	18.6	37.4	7.45	-107.5	4.37
B.P. EXIT	100.7	38.5	7.45	-103.0	4.39
PUMP INLET	100.7	38.5	7.45	-103.0	4.39
1ST STAGE EXIT	2298.3	69.9	7.45	35.8	4.42
JBV INLET	2252.4	70.3	3.73	35.8	4.39
JBV EXIT	1914.5	73.0	3.73	35.8	4.17
2ND STAGE EXIT	4129.8	100.4	3.72	166.2	4.36
PUMP EXIT	5894.9	128.6	3.72	291.2	4.38
COOLANT INLET	5836.0	129.0	3.72	291.2	4.35
COOLANT EXIT	5399.8	1031.1	3.72	3650.9	0.87
TBV INLET	5345.8	1031.4	0.19	3650.9	0.86
TBV EXIT	2004.7	1053.9	0.19	3650.9	0.34
O2 TRB INLET	5345.8	1031.4	3.53	3650.9	0.86
O2 TRB EXIT	4659.4	1002.4	3.53	3535.9	0.78
H2 TRB INLET	4659.4	1002.4	3.53	3535.9	0.78
H2 TRB EXIT	2128.3	859.5	3.53	2974.5	0.44
H2 TRB DIFFUSER	2103.1	859.6	3.53	2974.5	0.43
H2 BST TRB IN	2082.1	859.6	3.53	2974.5	0.43
H2 BST TRB OUT	2055.4	857.2	3.53	2964.9	0.43
H2 BST TRB DIFF	2050.3	857.3	3.53	2964.9	0.42
O2 BST TRB IN	2029.8	857.4	3.53	2964.9	0.42
O2 BST TRB OUT	2015.6	856.0	3.53	2959.8	0.42
O2 BST TRB DIFF	2014.8	856.0	3.53	2959.8	0.42
H2 TANK PRESS	18.6	878.8	0.0068	2994.3	0.0040
GOX HEAT EXCH IN	2004.7	865.9	3.71	2994.3	0.41
GOX HEAT EXCH OUT	1994.7	865.1	3.71	2991.6	0.41
MIXER HOT IN	1994.7	865.1	3.71	2991.6	0.41
MIXER COLD IN	1914.5	73.0	3.73	35.8	4.17
MIXER OUT	1894.9	452.6	7.44	1511.1	0.72
FSOV INLET	1894.9	452 [illegible]	7.44	1511.1	0.72
FSOV EXIT	1847.5	452.7	7.44	1511.1	0.71
CHAMBER INJ	1829.1	452.8	7.44	1511.1	0.70
CHAMBER	1701.4				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	16.0	162.7	44.7	61.9	70.99
B.P. EXIT	135.2	165.3	44.7	62.3	70.84
PUMP INLET	135.2	165.3	44.7	62.3	70.84
PUMP EXIT	2755.5	177.6	44.7	71.4	71.37
O2 TANK PRESS	16.0	400.0	0.076	204.7	0.12
OSOV INLET	2728.0	177.7	6.7	71.4	71.33
OSOV EXIT	1909.6	180.9	6.7	71.4	70.05
OCV INLET	2728.0	177.7	37.9	71.4	71.33
OCV EXIT	1909.6	180.9	37.9	71.4	70.05
CHAMBER INJ	1890.5	181.0	44.6	71.4	70.02
CHAMBER	1701.4				

* VALVE DATA *

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	338.	0.14	3.73	50.04
TBV	3341.	0.91	0.19	5.00
FSOV	47.	1.85	7.44	
OCV	818.	0.23	44.64	

* INJECTOR DATA *

INJECTOR	DELTA P	AREA	FLOW
FUEL	128.	1.19	7.44
LOX	189.	2.59	44.64

TABLE A-8. — SPLIT EXPANDER—1560°R HOT-WALL TEMPERATURE LIMIT (CONTINUED)

* TURBOMACHINERY PERFORMANCE DATA *

* H2 BOOST TURBINE *

EFFICIENCY (T/T)	0.874
EFFICIENCY (T/S)	0.698
SPEED (RPM)	41328.
MEAN DIA (IN)	2.12
EFF AREA (IN2)	1.53
U/C (ACTUAL)	0.553
MAX TIP SPEED	464.
STAGES	1
GAMMA	1.37
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.02
HORSEPOWER	48.
EXIT MACH NUMBER	0.06
SPECIFIC SPEED	110.57
SPECIFIC DIAMETER	0.78

* H2 BOOST PUMP *

EFFICIENCY	0.765
HORSEPOWER	48.
SPEED (RPM)	41328.
S SPEED	3046.
HEAD (FT)	2698.
DIA. (IN)	2.43
TIP SPEED	439.
VOL. FLOW	761.
HEAD COEF	0.450
FLOW COEF	0.201

* H2 TURBINE *

EFFICIENCY (T/T)	0.805
EFFICIENCY (T/S)	0.791
SPEED (RPM)	125000.
HORSEPOWER	2807.
MEAN DIA. (IN)	3.14
EFF AREA (IN2)	0.17
U/C (ACTUAL)	0.456
MAX TIP SPEED	1780.
STAGES	2
GAMMA	1.37
PRESS RATIO (T/T)	2.19
PRESS RATIO (T/S)	2.22
EXIT MACH NUMBER	0.13
SPECIFIC SPEED	27.82
SPECIFIC DIAMETER	2.28

* H2 PUMP *

	STAGE ONE	STAGE TWO	STAGE THREE
EFFICIENCY	0.664	0.592	0.598
HORSEPOWER	1463.	686.	658.
SPEED (RPM)	125000.	125000.	125000.
SS SPEED	11329.		
S SPEED	784.	637.	652.
HEAD (FT)	71728.	60089.	58151.
DIA. (IN)	3.78	3.50	3.50
TIP SPEED	2065.	1913.	1913.
VOL. FLOW	756.	383.	382.
HEAD COEF	0.541	0.528	0.511
FLOW COEF	0.096		
DIAMETER RATIO	0.333		
BEARING DN	3.00E+06		
SHAFT DIAMETER	24.00		

* O2 BOOST TURBINE *

EFFICIENCY (T/T)	0.867
EFFICIENCY (T/S)	0.804
SPEED (RPM)	11043.
MEAN DIA (IN)	5.83
EFF AREA (IN2)	2.11
U/C (ACTUAL)	0.553
MAX TIP SPEED	301.
STAGES	1
GAMMA	1.37
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	26.
EXIT MACH NUMBER	0.03
SPECIFIC SPEED	52.60
SPECIFIC DIAMETER	1.55

* O2 BOOST PUMP *

EFFICIENCY	0.764
HORSEPOWER	26.
SPEED (RPM)	11043.
S SPEED	3026.
HEAD (FT)	242.
DIA. (IN)	2.73
TIP SPEED	132.
VOL. FLOW	283.
HEAD COEF	0.450
FLOW COEF	0.200

* O2 TURBINE *

EFFICIENCY (T/T)	0.839
EFFICIENCY (T/S)	0.818
SPEED (RPM)	67248.
HORSEPOWER	575.
MEAN DIA (IN)	3.14
EFF AREA (IN2)	0.22
U/C (ACTUAL)	0.542
MAX TIP SPEED	961.
STAGES	2
GAMMA	1.37
PRESS RATIO (T/T)	1.15
PRESS RATIO (T/S)	1.15
EXIT MACH NUMBER	0.07
SPECIFIC SPEED	36.95
SPECIFIC DIAMETER	2.09

* O2 PUMP *

EFFICIENCY	0.747
HORSEPOWER	575.
SPEED (RPM)	67248.
SS SPEED	22352.
S SPEED	1819.
HEAD (FT)	5285.
DIA. (IN)	2.15
TIP SPEED	632.
VOL. FLOW	281.
HEAD COEF	0.426
FLOW COEF	0.154
DIAMETER RATIO	0.682
BEARING DN	1.34E+06
SHAFT DIAMETER	20.00

TABLE A-8. — SPLIT EXPANDER—1560°R HOT-WALL TEMPERATURE LIMIT (CONTINUED)

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************************************
* CHAMBER & NOZZLE HEAT TRANSFER   *
************************************

        ** CHAMBER DESIGN **

CHAMBER MATL/TYPE              COPPER/TUBULAR
WDA (LBM/SEC), CHAMBER FLOW       3.72
DPIN (PSID), INLET DELTA P       28.65
DP   (PSID), CHAMBER DELTA P    254.68
DPEX (PSID), EXIT DELTA P        75.32
DPT  (PSID), TOTAL DELTA P      358.64
QTOT (BTU/S), HEAT TRANSFER    8907.83
DTCH (R), DELTA TEMPERATURE     628.41
UTTM, ULTIMATE TEMP MARGIN      104.48
PRYS, MAX STRESS RATIO           59.47
THOT, MAX HOT WALL TEMPERATURE 1553.95
UTTS, THROAT MAX TEMPERATURE   1170.62
ASP,  ASPECT RATIO                1.50
ZI (IN), CHAMBER LENGTH          12.00
ARI, CONTRACTION RATIO            2.50
TN, NUMBER OF TUBES             120.00
```

TABLE A-9. — SPLIT EXPANDER—1660°R HOT-WALL TEMPERATURE LIMIT

ENGINE PERFORMANCE PARAMETERS

CHAMBER PRESSURE	1757.5
VAC ENGINE THRUST	25000.
TURBINE PRESSURE RATIO	2.600
TOTAL ENGINE FLOW RATE	52.08
DEL. VAC. ISP	480.1
THROAT AREA	6.96
NOZZLE AREA RATIO	1000.0
NOZZLE EXIT DIAMETER	94.13
ENGINE MIXTURE RATIO	6.00
ETA C*	0.993
CHAMBER COOLANT DP	458.
CHAMBER COOLANT DT	960.
NOZZLE/CHAMBER Q	13257.

ENGINE STATION CONDITIONS

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	18.6	37.4	7.45	-107.5	4.37
B.P. EXIT	100.5	38.5	7.45	-103.0	4.39
PUMP INLET	100.5	38.5	7.45	-103.0	4.39
1ST STAGE EXIT	2374.1	71.5	7.45	42.2	4.41
JBV INLET	2326.6	71.9	3.73	42.2	4.38
JBV EXIT	1977.6	74.7	3.73	42.2	4.15
2ND STAGE EXIT	4271.3	103.8	3.72	179.3	4.34
PUMP EXIT	6096.5	133.3	3.72	310.6	4.36
COOLANT INLET	6035.5	133.8	3.72	310.6	4.34
COOLANT EXIT	5577.6	1093.6	3.72	3874.4	0.85
TBV INLET	5521.8	1094.0	0.19	3874.4	0.84
TBV EXIT	2070.7	1117.4	0.19	3874.4	0.33
O2 TRB INLET	5521.8	1094.0	3.53	3874.4	0.84
O2 TRB EXIT	4828.1	1064.0	3.53	3755.5	0.77
H2 TRB INLET	4828.1	1064.0	3.53	3755.5	0.77
H2 TRB EXIT	2196.6	913.9	3.53	3166.9	0.43
H2 TRB DIFFUSER	2169.5	914.0	3.53	3166.9	0.42
H2 BST TRB IN	2147.8	914.0	3.53	3166.9	0.42
H2 BST TRB OUT	2121.9	911.6	3.53	3157.4	0.41
H2 BST TRB DIFF	2116.9	911.7	3.53	3157.4	0.41
O2 BST TRB IN	2095.8	911.8	3.53	3157.4	0.41
O2 BST TRB OUT	2081.9	910.4	3.53	3152.3	0.41
O2 BST TRB DIFF	2081.1	910.4	3.53	3152.3	0.41
H2 TANK PRESS	18.6	934.8	0.0064	3188.4	0.0037
GOX HEAT EXCH IN	2070.7	920.8	3.71	3188.4	0.40
GOX HEAT EXCH OUT	2060.4	920.1	3.71	3185.7	0.40
MIXER HOT IN	2060.4	920.1	3.71	3185.7	0.40
MIXER COLD IN	1977.6	74.7	3.73	42.2	4.15
MIXER OUT	1957.3	479.2	7.44	1611.4	0.71
FSOV INLET	1957.3	479.2	7.44	1611.4	0.71
FSOV EXIT	1908.4	479.4	7.44	1611.4	0.69
CHAMBER INJ	1889.3	479.5	7.44	1611.4	0.68
CHAMBER	1757.5				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	16.0	162.7	44.7	61.9	70.99
B.P. EXIT	135.2	165.3	44.7	62.3	70.84
PUMP INLET	135.2	165.3	44.7	62.3	70.84
PUMP EXIT	2846.4	178.0	44.7	71.7	71.39
O2 TANK PRESS	16.0	400.0	0.076	204.7	0.12
OSOV INLET	2817.9	178.2	6.7	71.7	71.34
OSOV EXIT	1972.6	181.4	6.7	71.7	70.02
OCV INLET	2817.9	178.2	37.9	71.7	71.34
OCV EXIT	1972.6	181.4	37.9	71.7	70.02
CHAMBER INJ	1952.8	181.5	44.6	71.7	69.99
CHAMBER	1757.5				

* VALVE DATA *

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	349.	0.14	3.73	50.04
TBV	3451.	0.01	0.19	5.00
FSOV	49.	1.84	7.44	
OCV	845.	0.23	44.64	

* INJECTOR DATA *

INJECTOR	DELTA P	AREA	FLOW
FUEL	132.	1.17	7.44
LOX	195.	0.57	44.64

TABLE A-9. — SPLIT EXPANDER—1660°R HOT-WALL TEMPERATURE LIMIT (CONTINUED)

TURBOMACHINERY PERFORMANCE DATA

H2 BOOST TURBINE

EFFICIENCY	(T/T)	0.874
EFFICIENCY	(T/S)	0.694
SPEED	(RPM)	41274.
MEAN DIA	(IN)	2.12
EFF AREA	(IN2)	1.57
U/C	(ACTUAL)	0.553
MAX TIP SPEED		465.
STAGES		1
GAMMA		1.43
PRESS RATIO	(T/T)	1.01
PRESS RATIO	(T/S)	1.02
HORSEPOWER		48.
EXIT MACH NUMBER		0.06
SPECIFIC SPEED		111.84
SPECIFIC DIAMETER		0.77

H2 BOOST PUMP

EFFICIENCY		0.766
HORSEPOWER		48.
SPEED	(RPM)	41274.
S SPEED		3049.
HEAD	(FT)	2690.
DIA.	(IN)	2.43
TIP SPEED		439.
VOL. FLOW		761.
HEAD COEF		0.450
FLOW COEF		0.201

H2 TURBINE

EFFICIENCY	(T/T)	0.801
EFFICIENCY	(T/S)	0.787
SPEED	(RPM)	125000.
HORSEPOWER		2943.
MEAN DIA.	(IN)	3.15
EFF AREA	(IN2)	0.17
U/C	(ACTUAL)	0.448
MAX TIP SPEED		1788.
STAGES		2
GAMMA		1.43
PRESS RATIO	(T/T)	2.20
PRESS RATIO	(T/S)	2.23
EXIT MACH NUMBER		0.13
SPECIFIC SPEED		26.81
SPECIFIC DIAMETER		2.31

H2 PUMP

	STAGE ONE	STAGE TWO	STAGE THREE
EFFICIENCY	0.658	0.585	0.591
HORSEPOWER	1530.	722.	691.
SPEED (RPM)	125000.	125000.	125000.
SS SPEED	11352.		
S SPEED	764.	620.	635.
HEAD (FT)	74371.	62500.	60411.
DIA. (IN)	3.84	3.57	3.57
TIP SPEED	2098.	1949.	1949.
VOL. FLOW	759.	384.	383.
HEAD COEF	0.543	0.529	0.512
FLOW COEF	0.094		
DIAMETER RATIO	0.328		
BEARING DN	3.00E+06		
SHAFT DIAMETER	24.00		

O2 BOOST TURBINE

EFFICIENCY	(T/T)	0.867
EFFICIENCY	(T/S)	0.804
SPEED	(RPM)	11043.
MEAN DIA	(IN)	5.83
EFF AREA	(IN2)	2.17
U/C	(ACTUAL)	0.553
MAX TIP SPEED		301.
STAGES		1
GAMMA		1.43
PRESS RATIO	(T/T)	1.01
PRESS RATIO	(T/S)	1.01
HORSEPOWER		26.
EXIT MACH NUMBER		0.03
SPECIFIC SPEED		53.35
SPECIFIC DIAMETER		1.53

O2 BOOST PUMP

EFFICIENCY		0.764
HORSEPOWER		26.
SPEED	(RPM)	11043.
S SPEED		3026.
HEAD	(FT)	242.
DIA.	(IN)	2.73
TIP SPEED		132.
VOL. FLOW		283.
HEAD COEF		0.450
FLOW COEF		0.200

O2 TURBINE

EFFICIENCY	(T/T)	0.839
EFFICIENCY	(T/S)	0.818
SPEED	(RPM)	68209.
HORSEPOWER		595.
MEAN DIA	(IN)	3.15
EFF AREA	(IN2)	0.22
U/C	(ACTUAL)	0.544
MAX TIP SPEED		980.
STAGES		2
GAMMA		1.43
PRESS RATIO	(T/T)	1.14
PRESS RATIO	(T/S)	1.15
EXIT MACH NUMBER		0.07
SPECIFIC SPEED		36.90
SPECIFIC DIAMETER		2.10

O2 PUMP

EFFICIENCY		0.747
HORSEPOWER		595.
SPEED	(RPM)	68209.
SS SPEED		22671.
S SPEED		1799.
HEAD	(FT)	5467.
DIA.	(IN)	2.16
TIP SPEED		642.
VOL. FLOW		281.
HEAD COEF		0.426
FLOW COEF		0.153
DIAMETER RATIO		0.681
BEARING DN		1.35E+06
SHAFT DIAMETER		20.00

TABLE A-9. — SPLIT EXPANDER—1660°R HOT-WALL TEMPERATURE LIMIT (CONTINUED)

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***********************************
* CHAMBER & NOZZLE HEAT TRANSFER  *
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       ** CHAMBER DESIGN **

CHAMBER MATL/TYPE               COPPER/TUBULAR
WDA (LBM/SEC), CHAMBER FLOW         3.72
DPIN (PSID), INLET DELTA P         32.10
DP   (PSID), CHAMBER DELTA P      259.12
DPEX (PSID), EXIT DELTA P          86.68
DPT  (PSID), TOTAL DELTA P        377.90
QTOT (BTU/S), HEAT TRANSFER      9608.75
DTCH (R), DELTA TEMPERATURE       680.87
UTTM, ULTIMATE TEMP MARGIN         94.10
PRYS, MAX STRESS RATIO             60.47
THOT, MAX HOT WALL TEMPERATURE  1601.81
UTTS, THROAT MAX TEMPERATURE    1077.79
ASP,  ASPECT RATIO                  1.50
ZI (IN), CHAMBER LENGTH            13.30
ARI, CONTRACTION RATIO              2.50
TN, NUMBER OF TUBES               120.00
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TABLE A-10. — SPLIT EXPANDER—35-PERCENT BYPASS/18-PERCENT ENHANCEMENT—FOUR-STAGE PUMP

ENGINE PERFORMANCE PARAMETERS

CHAMBER PRESSURE	1922.2
VAC ENGINE THRUST	25000.
TURBINE PRESSURE RATIO	2.400
TOTAL ENGINE FLOW RATE	52.07
DEL. VAC. ISP	480.1
THROAT AREA	6.37
NOZZLE AREA RATIO	1000.0
NOZZLE EXIT DIAMETER	90.04
ENGINE MIXTURE RATIO	6.00
ETA C*	0.993
CHAMBER COOLANT DP	551.
CHAMBER COOLANT DT	839.
NOZZLE/CHAMBER Q	15186.

ENGINE STATION CONDITIONS

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	18.6	37.4	7.45	-107.5	4.37
B.P. EXIT	100.5	38.5	7.45	-103.0	4.39
PUMP INLET	100.5	38.5	7.45	-103.0	4.39
1ST STAGE EXIT	1339.4	53.2	7.45	-33.0	4.50
2ND STAGE EXIT	2596.5	67.4	7.45	36.8	4.59
JBV INLET	2544.5	67.9	2.60	36.8	4.56
JBV EXIT	2162.9	71.4	2.60	36.8	4.32
3RD STAGE EXIT	4486.0	95.5	4.85	160.7	4.56
PUMP EXIT	6361.0	121.5	4.85	281.1	4.60
COOLANT INLET	6297.4	122.0	4.85	281.1	4.57
COOLANT EXIT	5746.1	961.2	4.85	3413.3	0.98
TBV INLET	5688.6	961.5	0.24	3413.3	0.97
TBV EXIT	2265.0	984.0	0.24	3413.3	0.41
O2 TRB INLET	5688.6	961.5	4.61	3413.3	0.97
O2 TRB EXIT	4980.9	937.1	4.61	3313.1	0.88
O2 TRB DIFF	4952.9	937.2	0.000	3313.1	0.88
1ST H2 TRB INLET	4853.8	937.7	4.61	3313.1	0.86
2ND H2 TRB INLET	3552.4	882.1	4.61	3087.0	0.69
H2 TRB EXIT	2422.2	816.8	4.61	2829.8	0.52
H2 TRB DIFFUSER	2368.6	817.1	4.61	2829.8	0.51
H2 BST TRB IN	2344.9	817.1	4.61	2829.8	0.51
H2 BST TRB OUT	2320.4	815.4	4.61	2822.5	0.50
H2 BST TRB DIFF	2313.4	815.4	4.61	2822.5	0.50
O2 BST TRB IN	2290.2	815.6	4.61	2822.5	0.50
O2 BST TRB OUT	2277.4	814.5	4.61	2818.6	0.49
O2 BST TRB DIFF	2276.4	814.5	4.61	2818.6	0.49
H2 TANK PRESS	18.6	837.2	0.0072	2848.3	0.0042
GOX HEAT EXCH IN	2265.0	823.0	4.84	2848.3	0.49
GOX HEAT EXCH OUT	2253.7	822.5	4.84	2846.3	0.48
MIXER HOT IN	2253.7	822.5	4.84	2846.3	0.48
MIXER COLD IN	2162.9	71.4	2.60	36.8	4.32
MIXER OUT	2141.0	548.0	7.44	1865.1	0.68
FSOV INLET	2141.0	548.0	7.44	1865.1	0.68
FSOV EXIT	2087.5	548.2	7.44	1865.1	0.66
CHAMBER INJ	2066.6	548.3	7.44	1865.1	0.65
CHAMBER	1922.2				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	16.0	162.7	44.7	61.9	70.99
B.P. EXIT	135.2	165.3	44.7	62.3	70.84
PUMP INLET	135.2	165.3	44.7	62.3	70.84
PUMP EXIT	3113.0	179.3	44.7	72.7	71.43
O2 TANK PRESS	16.0	400.0	0.076	204.7	0.12
OSOV INLET	3081.9	179.4	6.7	72.7	71.38
OSOV EXIT	2157.3	183.1	6.7	72.7	69.95
OCV INLET	3081.9	179.4	37.9	72.7	71.38
OCV EXIT	2157.3	183.1	37.9	72.7	69.95
CHAMBER INJ	2135.8	183.2	44.6	72.7	69.92
CHAMBER	1922.2				

* VALVE DATA *

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	382.	0.09	2.60	34.89
TBV	3424.	0.01	0.24	5.00
FSOV	54.	1.80	7.44	
OCV	925.	0.22	44.63	

* INJECTOR DATA *

INJECTOR	DELTA P	AREA	FLOW
FUEL	144.	1.14	7.44
LOX	214.	0.55	44.63

TABLE A-10. — SPLIT EXPANDER—35-PERCENT BYPASS/18-PERCENT ENHANCEMENT—FOUR-STAGE PUMP (CONTINUED)

TURBOMACHINERY PERFORMANCE DATA

H2 BOOST TURBINE

EFFICIENCY (T/T)	0.865
EFFICIENCY (T/S)	0.625
SPEED (RPM)	41268.
MEAN DIA (IN)	1.86
EFF AREA (IN2)	1.91
U/C (ACTUAL)	0.553
MAX TIP SPEED	429.
STAGES	1
GAMMA	1.42
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	48.
EXIT MACH NUMBER	0.07
SPECIFIC SPEED	130.28
SPECIFIC DIAMETER	0.66

H2 BOOST PUMP

EFFICIENCY	0.766
HORSEPOWER	48.
SPEED (RPM)	41268.
S SPEED	3049.
HEAD (FT)	2689.
DIA. (IN)	2.43
TIP SPEED	439.
VOL. FLOW	761.
HEAD COEF	0.450
FLOW COEF	0.201

H2 TURBINES

	TURBINE 1	TURBINE 2
EFFICIENCY (T/T)	0.821	0.817
EFFICIENCY (T/S)	0.781	0.761
SPEED (RPM)	125000.	125000.
HORSEPOWER	1473.	1676.
MEAN DIA. (IN)	2.64	2.64
EFF AREA (IN2)	0.23	0.29
U/C (ACTUAL)	0.428	0.40
MAX TIP SPEED	1510.	1524.
STAGES	1	1
GAMMA	1.42	1.42
PRESS RATIO (T/T)	1.37	1.47
PRESS RATIO (T/S)	1.39	1.51
EXIT MACH NUMBER	0.14	0.18
SPECIFIC SPEED	29.82	31.10
SPECIFIC DIAMETER	2.04	1.82

H2 PUMP

	STAGE 1	STAGE 2	STAGE 3	STAGE 4
EFFICIENCY	0.733	0.732	0.626	0.630
HORSEPOWER	737.	736.	850.	825.
SPEED (RPM)	125000.	125000.	125000.	125000.
SS SPEED	11354.			
S SPEED	1206.	1197.	709.	719.
HEAD (FT)	39940.	39800.	60397.	58949.
DIA. (IN)	2.95	2.95	3.51	3.51
TIP SPEED	1610.	1610.	1918.	1918.
VOL. FLOW	743.	729.	477.	474.
HEAD COEF	0.496	0.494	0.528	0.515
FLOW COEF	0.123			
DIAMETER RATIO	0.427			
BEARING DN	3.00E+06			
SHAFT DIAMETER	24.00			

O2 BOOST TURBINE

EFFICIENCY (T/T)	0.875
EFFICIENCY (T/S)	0.792
SPEED (RPM)	11043.
MEAN DIA (IN)	5.11
EFF AREA (IN2)	2.65
U/C (ACTUAL)	0.553
MAX TIP SPEED	271.
STAGES	1
GAMMA	1.42
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	26.
EXIT MACH NUMBER	0.03
SPECIFIC SPEED	66.42
SPECIFIC DIAMETER	1.25

O2 BOOST PUMP

EFFICIENCY	0.764
HORSEPOWER	26.
SPEED (RPM)	11043.
S SPEED	3026.
HEAD (FT)	242.
DIA. (IN)	2.73
TIP SPEED	132.
VOL. FLOW	283.
HEAD COEF	0.450
FLOW COEF	0.200

O2 TURBINE

EFFICIENCY (T/T)	0.813
EFFICIENCY (T/S)	0.770
SPEED (RPM)	70570.
HORSEPOWER	654.
MEAN DIA (IN)	2.05
EFF AREA (IN2)	0.26
U/C (ACTUAL)	0.398
MAX TIP SPEED	691.
STAGES	2
GAMMA	1.42
PRESS RATIO (T/T)	1.14
PRESS RATIO (T/S)	1.15
EXIT MACH NUMBER	0.09
SPECIFIC SPEED	42.30
SPECIFIC DIAMETER	1.33

O2 PUMP

EFFICIENCY	0.746
HORSEPOWER	654.
SPEED (RPM)	70570.
SS SPEED	23455.
S SPEED	1735.
HEAD (FT)	6001.
DIA. (IN)	2.17
TIP SPEED	669.
VOL. FLOW	281.
HEAD COEF	0.431
FLOW COEF	0.150
DIAMETER RATIO	0.679
BEARING DN	1.41E+06
SHAFT DIAMETER	20.00

C-2

TABLE A-10. — SPLIT EXPANDER—35-PERCENT BYPASS/18-PERCENT ENHANCEMENT—FOUR-STAGE PUMP (CONTINUED)

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************************************
* CHAMBER & NOZZLE HEAT TRANSFER  *
************************************

       ** CHAMBER DESIGN **

CHAMBER MATL/TYPE              COPPER/TUBULAR
WDA (LBM/SEC), CHAMBER FLOW         4.85
DPIN (PSID), INLET DELTA P         68.30
DP   (PSID), CHAMBER DELTA P      266.23
DPEX (PSID), EXIT DELTA P         133.05
DPT  (PSID), TOTAL DELTA P        467.57
QTOT (BTU/S), HEAT TRANSFER     11370.42
DTCH (R), DELTA TEMPERATURE       616.65
UTTM, ULTIMATE TEMP MARGIN        168.79
PRYS, MAX STRESS RATIO             61.11
THOT, MAX HOT WALL TEMPERATURE  1459.87
UTTS, THROAT MAX TEMPERATURE    1050.54
ASP,  ASPECT RATIO                  3.00
ZI (IN), CHAMBER LENGTH            16.25
ARI, CONTRACTION RATIO              3.00
TN, NUMBER OF TUBES               120.00
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TABLE A-11. — SPLIT EXPANDER—35-PERCENT BYPASS/30-PERCENT ENHANCEMENT—FOUR-STAGE PUMP

ENGINE PERFORMANCE PARAMETERS

CHAMBER PRESSURE	2049.6
VAC ENGINE THRUST	25000.
TURBINE PRESSURE RATIO	2.350
TOTAL ENGINE FLOW RATE	52.07
DEL. VAC. ISP	480.1
THROAT AREA	5.97
NOZZLE AREA RATIO	1000.0
NOZZLE EXIT DIAMETER	87.21
ENGINE MIXTURE RATIO	6.00
ETA C*	0.993
CHAMBER COOLANT DP	726.
CHAMBER COOLANT DT	946.
NOZZLE/CHAMBER Q	17011.

ENGINE STATION CONDITIONS

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	18.6	37.4	7.44	-107.5	4.37
B.P. EXIT	100.9	38.5	7.44	-103.0	4.39
PUMP INLET	100.9	38.5	7.44	-103.0	4.39
1ST STAGE EXIT	1426.1	54.5	7.44	-27.6	4.50
2ND STAGE EXIT	2768.6	69.9	7.44	47.6	4.58
JBV INLET	2713.2	70.4	2.60	47.6	4.55
JBV EXIT	2306.3	74.0	2.60	47.6	4.31
3RD STAGE EXIT	4792.2	101.0	4.85	183.6	4.54
PUMP EXIT	6792.8	129.4	4.85	315.2	4.58
COOLANT INLET	6724.9	130.0	4.85	315.2	4.55
COOLANT EXIT	5999.1	1076.3	4.85	3822.7	0.92
TBV INLET	5939.1	1076.6	0.24	3822.7	0.91
TBV EXIT	2415.0	1100.1	0.24	3822.7	0.39
O2 TRB INLET	5939.1	1076.6	4.61	3822.7	0.91
O2 TRB EXIT	5230.3	1050.5	4.61	3715.4	0.83
O2 TRB DIFF	5200.7	1050.6	0.000	3715.4	0.83
1ST H2 TRB INLET	5096.7	1051.3	4.61	3715.4	0.81
2ND H2 TRB INLET	3770.5	990.4	4.61	3472.0	0.65
H2 TRB EXIT	2585.8	918.0	4.61	3190.4	0.49
H2 TRB DIFFUSER	2520.6	918.4	4.61	3190.4	0.48
H2 BST TRB IN	2495.4	918.4	4.61	3190.4	0.48
H2 BST TRB OUT	2472.0	916.6	4.61	3183.1	0.47
H2 BST TRB DIFF	2465.0	916.7	4.61	3183.1	0.47
O2 BST TRB IN	2440.3	916.8	4.61	3183.1	0.47
O2 BST TRB OUT	2428.2	915.8	4.61	3179.1	0.47
O2 BST TRB DIFF	2427.2	915.8	4.61	3179.1	0.47
H2 TANK PRESS	18.6	941.4	0.0063	3211.3	0.0037
GOX HEAT EXCH IN	2415.0	925.1	4.84	3211.3	0.46
GOX HEAT EXCH OUT	2403.0	924.6	4.84	3209.2	0.46
MIXER HOT IN	2403.0	924.6	4.84	3209.2	0.46
MIXER COLD IN	2306.3	74.0	2.60	47.6	4.31
MIXER OUT	2282.8	613.6	7.44	2106.3	0.65
FSOV INLET	2282.8	613.6	7.44	2106.3	0.65
FSOV EXIT	2225.7	613.9	7.44	2106.3	0.63
CHAMBER INJ	2203.5	614.0	7.44	2106.3	0.62
CHAMBER	2049.6				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	16.0	162.7	44.7	61.9	70.99
B.P. EXIT	135.2	165.3	44.7	62.3	70.84
PUMP INLET	135.2	165.3	44.7	62.3	70.84
PUMP EXIT	3319.3	180.3	44.7	73.4	71.46
O2 TANK PRESS	16.0	400.0	0.076	204.7	0.12
OSOV INLET	3286.1	180.4	6.7	73.4	71.41
OSOV EXIT	2300.3	184.3	6.7	73.4	69.90
OCV INLET	3286.1	180.4	37.9	73.4	71.41
OCV EXIT	2300.3	184.3	37.9	73.4	69.90
CHAMBER INJ	2277.3	184.4	44.6	73.4	69.86
CHAMBER	2049.6				

* VALVE DATA *

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	407.	0.09	2.60	34.86
TBV	3524.	0.01	0.24	5.00
FSOV	57.	1.79	7.44	
OCV	986.	0.21	44.63	

* INJECTOR DATA *

INJECTOR	DELTA P	AREA	FLOW
FUEL	154.	1.14	7.44
LOX	228.	0.53	44.63

TABLE A-11. — SPLIT EXPANDER—35-PERCENT BYPASS/30-PERCENT ENHANCEMENT—FOUR-STAGE PUMP (CONTINUED)

TURBOMACHINERY PERFORMANCE DATA

H2 BOOST TURBINE

EFFICIENCY (T/T)	0.864
EFFICIENCY (T/S)	0.616
SPEED (RPM)	41371.
MEAN DIA (IN)	1.86
EFF AREA (IN2)	2.01
U/C (ACTUAL)	0.553
MAX TIP SPEED	433.
STAGES	1
GAMMA	1.41
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	48.
EXIT MACH NUMBER	0.07
SPECIFIC SPEED	132.22
SPECIFIC DIAMETER	0.65

H2 BOOST PUMP

EFFICIENCY	0.765
HORSEPOWER	48.
SPEED (RPM)	41371.
S SPEED	3044.
HEAD (FT)	2703.
DIA. (IN)	2.43
TIP SPEED	440.
VOL. FLOW	761.
HEAD COEF	0.450
FLOW COEF	0.201

H2 TURBINES

	TURBINE 1	TURBINE 2
EFFICIENCY (T/T)	0.815	0.808
EFFICIENCY (T/S)	0.771	0.745
SPEED (RPM)	125000.	125000.
HORSEPOWER	1587.	1836.
MEAN DIA. (IN)	2.65	2.65
EFF AREA (IN2)	0.23	0.29
U/C (ACTUAL)	0.415	0.39
MAX TIP SPEED	1519.	1532.
STAGES	1	1
GAMMA	1.41	1.41
PRESS RATIO (T/T)	1.35	1.46
PRESS RATIO (T/S)	1.38	1.51
EXIT MACH NUMBER	0.14	0.20
SPECIFIC SPEED	28.78	29.40
SPECIFIC DIAMETER	2.03	1.83

H2 PUMP

	STAGE 1	STAGE 2	STAGE 3	STAGE 4
EFFICIENCY	0.728	0.727	0.613	0.617
HORSEPOWER	795.	792.	933.	903.
SPEED (RPM)	125000.	125000.	125000.	125000.
SS SPEED	11312.			
S SPEED	1146.	1140.	673.	684.
HEAD (FT)	42722.	42535.	64869.	63154.
DIA. (IN)	3.03	3.03	3.63	3.63
TIP SPEED	1654.	1655.	1984.	1984.
VOL. FLOW	743.	729.	479.	476.
HEAD COEF	0.502	0.500	0.530	0.516
FLOW COEF	0.119			
DIAMETER RATIO	0.416			
BEARING DN	3.00E+06			
SHAFT DIAMETER	24.00			

O2 BOOST TURBINE

EFFICIENCY (T/T)	0.875
EFFICIENCY (T/S)	0.789
SPEED (RPM)	11043.
MEAN DIA (IN)	5.11
EFF AREA (IN2)	2.80
U/C (ACTUAL)	0.553
MAX TIP SPEED	272.
STAGES	1
GAMMA	1.41
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	26.
EXIT MACH NUMBER	0.03
SPECIFIC SPEED	68.10
SPECIFIC DIAMETER	1.22

O2 BOOST PUMP

EFFICIENCY	0.764
HORSEPOWER	26.
SPEED (RPM)	11043.
S SPEED	3026.
HEAD (FT)	242.
DIA. (IN)	2.73
TIP SPEED	132.
VOL. FLOW	283.
HEAD COEF	0.450
FLOW COEF	0.200

O2 TURBINE

EFFICIENCY (T/T)	0.811
EFFICIENCY (T/S)	0.766
SPEED (RPM)	72220.
HORSEPOWER	699.
MEAN DIA (IN)	2.05
EFF AREA (IN2)	0.27
U/C (ACTUAL)	0.394
MAX TIP SPEED	708.
STAGES	2
GAMMA	1.41
PRESS RATIO (T/T)	1.14
PRESS RATIO (T/S)	1.14
EXIT MACH NUMBER	0.09
SPECIFIC SPEED	42.29
SPECIFIC DIAMETER	1.31

O2 PUMP

EFFICIENCY	0.745
HORSEPOWER	699.
SPEED (RPM)	72220.
SS SPEED	24004.
S SPEED	1689.
HEAD (FT)	6414.
DIA. (IN)	2.18
TIP SPEED	688.
VOL. FLOW	281.
HEAD COEF	0.436
FLOW COEF	0.148
DIAMETER RATIO	0.678
BEARING DN	1.44E+06
SHAFT DIAMETER	20.00

TABLE A-12. — SPLIT EXPANDER—50-PERCENT BYPASS/18-PERCENT ENHANCEMENT—FOUR-STAGE PUMP

ENGINE PERFORMANCE PARAMETERS

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CHAMBER PRESSURE	1916.6
VAC ENGINE THRUST	25000.
TURBINE PRESSURE RATIO	2.400
TOTAL ENGINE FLOW RATE	52.07
DEL. VAC. ISP	480.1
THROAT AREA	6.39
NOZZLE AREA RATIO	1000.0
NOZZLE EXIT DIAMETER	90.17
ENGINE MIXTURE RATIO	6.00
ETA C*	0.993
CHAMBER COOLANT DP	593.
CHAMBER COOLANT DT	1073.
NOZZLE/CHAMBER Q	14715.

ENGINE STATION CONDITIONS

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* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	18.6	37.4	7.44	-107.5	4.37
B.P. EXIT	100.9	38.5	7.44	-103.0	4.39
PUMP INLET	100.9	38.5	7.44	-103.0	4.39
1ST STAGE EXIT	1335.6	53.1	7.44	-33.3	4.50
2ND STAGE EXIT	2588.9	67.3	7.44	36.3	4.59
JBV INLET	2537.2	67.8	3.72	36.3	4.56
JBV EXIT	2156.6	71.3	3.72	36.3	4.33
3RD STAGE EXIT	4515.9	99.8	3.72	173.5	4.49
PUMP EXIT	6386.2	129.2	3.72	304.7	4.49
COOLANT INLET	6322.3	129.7	3.72	304.7	4.46
COOLANT EXIT	5729.3	1202.3	3.72	4260.4	0.80
TBV INLET	5672.0	1202.6	0.19	4260.4	0.79
TBV EXIT	2258.5	1226.0	0.19	4260.4	0.33
O2 TRB INLET	5672.0	1202.6	3.53	4260.4	0.79
O2 TRB EXIT	4905.6	1170.2	3.53	4130.1	0.71
O2 TRB DIFF	4864.4	1170.3	0.000	4130.1	0.71
1ST H2 TRB INLET	4767.1	1170.8	3.53	4130.1	0.69
2ND H2 TRB INLET	3394.5	1097.2	3.53	3836.6	0.54
H2 TRB EXIT	2413.8	1023.3	3.53	3554.1	0.42
H2 TRB DIFFUSER	2361.1	1023.7	3.53	3554.1	0.41
H2 BST TRB IN	2337.5	1023.7	3.53	3554.1	0.41
H2 BST TRB OUT	2312.2	1021.3	3.53	3544.5	0.40
H2 BST TRB DIFF	2307.2	1021.3	3.53	3544.5	0.40
O2 BST TRB IN	2284.1	1021.5	3.53	3544.5	0.40
O2 BST TRB OUT	2270.6	1020.1	3.53	3539.3	0.40
O2 BST TRB DIFF	2269.8	1020.1	3.53	3539.3	0.40
H2 TANK PRESS	18.6	1046.5	0.0057	3575.4	0.0033
GOX HEAT EXCH IN	2258.5	1030.5	3.71	3575.4	0.39
GOX HEAT EXCH OUT	2247.2	1029.8	3.71	3572.7	0.39
MIXER HOT IN	2247.2	1029.8	3.71	3572.7	0.39
MIXER COLD IN	2156.6	71.3	3.72	36.3	4.33
MIXER OUT	2134.8	530.7	7.44	1802.0	0.69
FSOV INLET	2134.8	530.7	7.44	1802.0	0.69
FSOV EXIT	2081.5	530.9	7.44	1802.0	0.68
CHAMBER INJ	2060.6	531.0	7.44	1802.0	0.67
CHAMBER	1916.6				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	16.0	162.7	44.7	61.9	70.99
B.P. EXIT	135.2	165.3	44.7	62.3	70.84
PUMP INLET	135.2	165.3	44.7	62.3	70.84
PUMP EXIT	3103.9	179.3	44.7	72.6	71.43
O2 TANK PRESS	16.0	400.0	0.076	204.7	0.12
OSOV INLET	3072.9	179.4	6.7	72.6	71.38
OSOV EXIT	2151.0	183.0	6.7	72.6	69.96
OCV INLET	3072.9	179.4	37.9	72.6	71.38
OCV EXIT	2151.0	183.0	37.9	72.6	69.96
CHAMBER INJ	2129.5	183.1	44.6	72.6	69.92
CHAMBER	1916.6				

* VALVE DATA *

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	381.	0.13	3.72	50.03
TBV	3414.	0.01	0.19	5.00
FSOV	53.	1.78	7.44	
OCV	922.	0.22	44.63	

* INJECTOR DATA *

INJECTOR	DELTA P	AREA	FLOW
FUEL	144.	1.13	7.44
LOX	213.	0.55	44.63

TABLE A-12. — SPLIT EXPANDER—50-PERCENT BYPASS/18-PERCENT ENHANCEMENT—FOUR-STAGE PUMP (CONTINUED)

TURBOMACHINERY PERFORMANCE DATA

H2 BOOST TURBINE

EFFICIENCY (T/T)	0.873
EFFICIENCY (T/S)	0.691
SPEED (RPM)	41382.
MEAN DIA (IN)	2.12
EFF AREA (IN2)	1.61
U/C (ACTUAL)	0.553
MAX TIP SPEED	468.
STAGES	1
GAMMA	1.39
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	48.
EXIT MACH NUMBER	0.06
SPECIFIC SPEED	112.84
SPECIFIC DIAMETER	0.76

H2 BOOST PUMP

EFFICIENCY	0.765
HORSEPOWER	48.
SPEED (RPM)	41382.
S SPEED	3044.
HEAD (FT)	2705.
DIA. (IN)	2.43
TIP SPEED	440.
VOL. FLOW	761.
HEAD COEF	0.450
FLOW COEF	0.201

H2 TURBINES

	TURBINE 1	TURBINE 2
EFFICIENCY (T/T)	0.786	0.805
EFFICIENCY (T/S)	0.729	0.743
SPEED (RPM)	125000.	125000.
HORSEPOWER	1467.	1413.
MEAN DIA. (IN)	2.66	2.66
EFF AREA (IN2)	0.20	0.27
U/C (ACTUAL)	0.378	0.39
MAX TIP SPEED	1513.	1528.
STAGES	1	1
GAMMA	1.39	1.39
PRESS RATIO (T/T)	1.40	1.41
PRESS RATIO (T/S)	1.44	1.45
EXIT MACH NUMBER	0.17	0.18
SPECIFIC SPEED	23.43	28.05
SPECIFIC DIAMETER	2.20	1.91

H2 PUMP

	STAGE 1	STAGE 2	STAGE 3	STAGE 4
EFFICIENCY	0.734	0.733	0.581	0.588
HORSEPOWER	734.	733.	723.	690.
SPEED (RPM)	125000.	125000.	125000.	125000.
SS SPEED	11308.			
S SPEED	1209.	1200.	613.	629.
HEAD (FT)	39802.	39681.	62112.	59999.
DIA. (IN)	2.95	2.95	3.56	3.57
TIP SPEED	1608.	1608.	1946.	1946.
VOL. FLOW	743.	728.	372.	372.
HEAD COEF	0.495	0.494	0.528	0.510
FLOW COEF	0.123			
DIAMETER RATIO	0.428			
BEARING DN	3.00E+06			
SHAFT DIAMETER	24.00			

O2 BOOST TURBINE

EFFICIENCY (T/T)	0.868
EFFICIENCY (T/S)	0.804
SPEED (RPM)	11043.
MEAN DIA (IN)	5.83
EFF AREA (IN2)	2.23
U/C (ACTUAL)	0.553
MAX TIP SPEED	302.
STAGES	1
GAMMA	1.39
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	26.
EXIT MACH NUMBER	0.02
SPECIFIC SPEED	54.06
SPECIFIC DIAMETER	1.51

O2 BOOST PUMP

EFFICIENCY	0.764
HORSEPOWER	26.
SPEED (RPM)	11043.
S SPEED	3026.
HEAD (FT)	242.
DIA. (IN)	2.73
TIP SPEED	132.
VOL. FLOW	283.
HEAD COEF	0.450
FLOW COEF	0.200

O2 TURBINE

EFFICIENCY (T/T)	0.774
EFFICIENCY (T/S)	0.719
SPEED (RPM)	70496.
HORSEPOWER	652.
MEAN DIA (IN)	2.05
EFF AREA (IN2)	0.22
U/C (ACTUAL)	0.349
MAX TIP SPEED	683.
STAGES	2
GAMMA	1.39
PRESS RATIO (T/T)	1.16
PRESS RATIO (T/S)	1.17
EXIT MACH NUMBER	0.11
SPECIFIC SPEED	32.04
SPECIFIC DIAMETER	1.46

O2 PUMP

EFFICIENCY	0.746
HORSEPOWER	652.
SPEED (RPM)	70496.
SS SPEED	23430.
S SPEED	1737.
HEAD (FT)	5983.
DIA. (IN)	2.17
TIP SPEED	668.
VOL. FLOW	281.
HEAD COEF	0.431
FLOW COEF	0.150
DIAMETER RATIO	0.679
BEARING DN	1.41E+06
SHAFT DIAMETER	20.00

TABLE A-12. — SPLIT EXPANDER—50-PERCENT BYPASS/18-PERCENT ENHANCEMENT—FOUR-STAGE PUMP (CONTINUED)

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**********************************
* CHAMBER & NOZZLE HEAT TRANSFER *
**********************************

       ** CHAMBER DESIGN **

CHAMBER MATL/TYPE              COPPER/TUBULAR
WDA (LBM/SEC), CHAMBER FLOW         3.72
DPIN (PSID), INLET DELTA P         41.26
DP   (PSID), CHAMBER DELTA P      341.19
DPEX (PSID), EXIT DELTA P         127.02
DPT  (PSID), TOTAL DELTA P        509.47
QTOT (BTU/S), HEAT TRANSFER     10904.99
DTCH (R), DELTA TEMPERATURE       780.57
UTTM, ULTIMATE TEMP MARGIN        100.51
PRYS, MAX STRESS RATIO             63.03
THOT, MAX HOT WALL TEMPERATURE   1655.64
UTTS, THROAT MAX TEMPERATURE      938.93
ASP,  ASPECT RATIO                  1.50
ZI (IN), CHAMBER LENGTH            15.50
ARI, CONTRACTION RATIO              2.40
TN, NUMBER OF TUBES               120.00
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TABLE A-13. — SPLIT EXPANDER—50-PERCENT BYPASS/30-PERCENT ENHANCEMENT—FOUR-STAGE PUMP

ENGINE PERFORMANCE PARAMETERS

CHAMBER PRESSURE	2161.7
VAC ENGINE THRUST	25000.
TURBINE PRESSURE RATIO	2.300
TOTAL ENGINE FLOW RATE	52.07
DEL. VAC. ISP	480.1
THROAT AREA	5.67
NOZZLE AREA RATIO	1000.0
NOZZLE EXIT DIAMETER	84.94
ENGINE MIXTURE RATIO	6.00
ETA C*	0.993
CHAMBER COOLANT DP	1017.
CHAMBER COOLANT DT	1370.
NOZZLE/CHAMBER Q	18631.

ENGINE STATION CONDITIONS

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	18.6	37.4	7.44	-107.5	4.37
B.P. EXIT	100.7	38.5	7.44	-103.0	4.39
PUMP INLET	100.7	38.5	7.44	-103.0	4.39
1ST STAGE EXIT	1501.9	55.6	7.44	-22.7	4.50
2ND STAGE EXIT	2920.1	72.0	7.44	57.3	4.58
JBV INLET	2861.7	72.6	3.72	57.3	4.55
JBV EXIT	2432.4	76.4	3.72	57.3	4.30
3RD STAGE EXIT	5143.2	112.1	3.72	224.1	4.45
PUMP EXIT	7281.6	147.2	3.72	382.2	4.44
COOLANT INLET	7208.8	147.7	3.72	382.2	4.42
COOLANT EXIT	6191.4	1518.0	3.72	5390.6	0.69
TBV INLET	6129.5	1518.4	0.19	5390.6	0.69
TBV EXIT	2546.4	1543.4	0.19	5390.6	0.30
O2 TRB INLET	6129.5	1518.4	3.53	5390.6	0.69
O2 TRB EXIT	5376.6	1481.7	3.53	5242.6	0.62
O2 TRB DIFF	5331.8	1482.0	0.000	5242.6	0.62
1ST H2 TRB INLET	5225.1	1482.7	3.53	5242.6	0.61
2ND H2 TRB INLET	3815.6	1397.3	3.53	4904.9	0.48
H2 TRB EXIT	2733.0	1308.6	3.53	4562.9	0.37
H2 TRB DIFFUSER	2651.3	1309.2	3.53	4562.9	0.36
H2 BST TRB IN	2624.8	1309.2	3.53	4562.9	0.36
H2 BST TRB OUT	2602.6	1306.8	3.53	4553.4	0.36
H2 BST TRB DIFF	2597.7	1306.9	3.53	4553.4	0.35
O2 BST TRB IN	2571.7	1307.1	3.53	4553.4	0.35
O2 BST TRB OUT	2559.9	1305.7	3.53	4548.2	0.35
O2 BST TRB DIFF	2559.2	1305.7	3.53	4548.2	0.35
H2 TANK PRESS	18.6	1337.1	0.0045	4590.4	0.0026
GOX HEAT EXCH IN	2546.4	1317.8	3.72	4590.4	0.35
GOX HEAT EXCH OUT	2533.6	1317.1	3.72	4587.7	0.34
MIXER HOT IN	2533.6	1317.1	3.72	4587.7	0.34
MIXER COLD IN	2432.4	76.4	3.72	57.3	4.30
MIXER OUT	2407.0	672.9	7.44	2320.3	0.62
FSOV INLET	2407.0	672.9	7.44	2320.3	0.62
FSOV EXIT	2346.8	673.2	7.44	2320.3	0.61
CHAMBER INJ	2323.3	673.4	7.44	2320.3	0.60
CHAMBER	2161.7				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
B.P. INLET	16.0	162.7	44.7	61.9	70.99
B.P. EXIT	135.2	165.3	44.7	62.3	70.84
PUMP INLET	135.2	165.3	44.7	62.3	70.84
PUMP EXIT	3500.8	181.1	44.7	74.0	71.48
O2 TANK PRESS	16.0	400.0	0.076	204.7	0.12
OSOV INLET	3465.8	181.3	6.7	74.0	71.43
OSOV EXIT	2426.0	185.5	6.7	74.0	69.85
OCV INLET	3465.8	181.3	37.9	74.0	71.43
OCV EXIT	2426.0	185.5	37.9	74.0	69.85
CHAMBER INJ	2401.8	185.6	44.6	74.0	69.81
CHAMBER	2161.7				

* VALVE DATA *

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	429.	0.13	3.72	50.02
TBV	3583.	0.01	0.19	5.00
FSOV	60.	1.77	7.44	
OCV	1040.	0.21	44.63	

* INJECTOR DATA *

INJECTOR	DELTA P	AREA	FLOW
FUEL	162.	1.13	7.44
LOX	240.	0.52	44.63

TABLE A-13. — SPLIT EXPANDER—50-PERCENT BYPASS/30-PERCENT ENHANCEMENT—FOUR-STAGE PUMP (CONTINUED)

* TURBOMACHINERY PERFORMANCE DATA *

* H2 BOOST TURBINE *

EFFICIENCY (T/T)	0.871
EFFICIENCY (T/S)	0.673
SPEED (RPM)	41324.
MEAN DIA (IN)	2.12
EFF AREA (IN2)	1.84
U/C (ACTUAL)	0.553
MAX TIP SPEED	474.
STAGES	1
GAMMA	1.41
PRESS RATIO (T/T)	1.01
PRESS RATIO (T/S)	1.01
HORSEPOWER	48.
EXIT MACH NUMBER	0.06
SPECIFIC SPEED	118.14
SPECIFIC DIAMETER	0.73

* H2 BOOST PUMP *

EFFICIENCY	0.765
HORSEPOWER	48.
SPEED (RPM)	41324.
S SPEED	3047.
HEAD (FT)	2696.
DIA. (IN)	2.43
TIP SPEED	439.
VOL. FLOW	761.
HEAD COEF	0.450
FLOW COEF	0.201

* H2 TURBINES *

	TURBINE 1	TURBINE 2
EFFICIENCY (T/T)	0.770	0.781
EFFICIENCY (T/S)	0.699	0.701
SPEED (RPM)	125000.	125000.
HORSEPOWER	1689.	1710.
MEAN DIA. (IN)	2.68	2.68
EFF AREA (IN2)	0.20	0.27
U/C (ACTUAL)	0.355	0.35
MAX TIP SPEED	1527.	1541.
STAGES	1	1
GAMMA	1.41	1.41
PRESS RATIO (T/T)	1.37	1.40
PRESS RATIO (T/S)	1.42	1.45
EXIT MACH NUMBER	0.19	0.21
SPECIFIC SPEED	21.78	24.79
SPECIFIC DIAMETER	2.18	1.92

* H2 PUMP *

	STAGE 1	STAGE 2	STAGE 3	STAGE 4
EFFICIENCY	0.723	0.722	0.556	0.563
HORSEPOWER	846.	843.	877.	833.
SPEED (RPM)	125000.	125000.	125000.	125000.
SS SPEED	11332.			
S SPEED	1099.	1093.	551.	568.
HEAD (FT)	45180.	44930.	72054.	69296.
DIA. (IN)	3.10	3.10	3.83	3.83
TIP SPEED	1693.	1693.	2088.	2089.
VOL. FLOW	743.	729.	375.	376.
HEAD COEF	0.507	0.504	0.532	0.511
FLOW COEF	0.117			
DIAMETER RATIO	0.406			
BEARING DN	3.00E+06			
SHAFT DIAMETER	24.00			

* O2 BOOST TURBINE *

EFFICIENCY (T/T)	0.870
EFFICIENCY (T/S)	0.801
SPEED (RPM)	11044.
MEAN DIA (IN)	5.83
EFF AREA (IN2)	2.54
U/C (ACTUAL)	0.553
MAX TIP SPEED	304.
STAGES	1
GAMMA	1.41
PRESS RATIO (T/T)	1.00
PRESS RATIO (T/S)	1.01
HORSEPOWER	26.
EXIT MACH NUMBER	0.02
SPECIFIC SPEED	57.47
SPECIFIC DIAMETER	1.42

* O2 BOOST PUMP *

EFFICIENCY	0.764
HORSEPOWER	26.
SPEED (RPM)	11044.
S SPEED	3026.
HEAD (FT)	242.
DIA. (IN)	2.73
TIP SPEED	132.
VOL. FLOW	283.
HEAD COEF	0.450
FLOW COEF	0.200

* O2 TURBINE *

EFFICIENCY (T/T)	0.770
EFFICIENCY (T/S)	0.710
SPEED (RPM)	73632.
HORSEPOWER	740.
MEAN DIA (IN)	2.05
EFF AREA (IN2)	0.24
U/C (ACTUAL)	0.342
MAX TIP SPEED	716.
STAGES	2
GAMMA	1.41
PRESS RATIO (T/T)	1.14
PRESS RATIO (T/S)	1.15
EXIT MACH NUMBER	0.11
SPECIFIC SPEED	32.22
SPECIFIC DIAMETER	1.41

* O2 PUMP *

EFFICIENCY	0.745
HORSEPOWER	740.
SPEED (RPM)	73632.
SS SPEED	24472.
S SPEED	1652.
HEAD (FT)	6777.
DIA. (IN)	2.19
TIP SPEED	704.
VOL. FLOW	281.
HEAD COEF	0.440
FLOW COEF	0.146
DIAMETER RATIO	0.677
BEARING DN	1.47E+06
SHAFT DIAMETER	20.00

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16. Abstract
The use of copper tubular thrust chambers is particularly important in a high-performance expander cycle space engine. High performance requires high combustion chamber pressure. Expander cycle engines are limited in chamber pressure by the amount of regenerative heat available to drive the turbomachinery. Tubular chambers have more surface area than flat wall chambers (milled-channel construction),and this extra surface area provides enhanced heat transfer for additional energy to power the cycle. The Tubular Copper Thrust Chamber Design Study was divided into two primary technical activities: (1) a Thermal Analysis and Sensitivity Study and (2) a Preliminary Design of a selected thrust chamber configuration. The thermal analysis consisted of a statistical optimization to determine the optimum tube geometry, tube booking, thrust chamber geometry, and cooling routing to achieve the maximum upper limit chamber pressure for a 25,000-pound thrust engine. Two cycle types, a split expander cycle and full expander cycle with a regenerator, were considered. The goal of the preliminary design was to define a tubular thrust chamber that would demonstrate the inherent advantages of copper tube construction in full-scale hardware. The Advanced Expander Test Bed (AETB) was selected as the most appropriate vehicle for the demonstration. The AETB is being designed with a 25-percent uprated design point relative to its normal operating point. The design point is 25,000 lb thrust at 1500 psia chamber pressure, and the normal operating point is 20,000 lb thrust at 1200 psia. The thrust chamber has a contraction ratio of 3 to 1 and a conical exhaust nozzle expanding to an area ratio of 2 to 1. A heat transfer enhancement of 18 percent is predicted to increase achievable chamber pressure to 1755 psia (or 11 percent) for the AETB with its current three-stage fuel pump configuration. The preliminary design effort produced a layout drawing for a tubular thrust chamber that is 3 inches shorter than the AETB milled channel chamber but is predicted to provide a 5 percent increase in overall heat transfer. Testing this chamber in the AETB would confirm the inherent advantages of tubular chamber construction and heat transfer.

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